17

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TABLE OF CONTENTS

PAGE

SECRETARY'S NOTES 657

TECHNOLOGY OF THE FIFTH WHEEL
CAPTAIN R. E. W. HARRISON, USNR 671

RECURRING MACHINE TOOL PROCUREMENT CRISES IN U. S. OPERATIONAL MANAGEMENT
CAPTAIN R. E. W. HARRISON, USNR 675

COMBINATION PROPULSION PLANTS FOR NAVAL VESSELS
American Society of Mechanical Engineers in Los Angeles, California, 28 June 1953 681

INDUSTRIAL NUCLEAR POWER—PART I - II - III - IV
"Nucleonics", McGraw-Hill Publishing Co., May 1953 688

TRANSISTORS
CLARENCE KABELE 707

ATOMIC PROPULSION—WITH SPECIAL REFERENCE TO MARINE PROPULSION
Transactions of the Institute of Marine Engineers, April 1953 715

"DELTIC" HIGH-SPEED MARINE DIESEL ENGINE
Engineering, May 1, 1953 727

THE EFFECT OF RADIAL-PITCH VARIATION ON THE PERFORMANCE OF A MARINE PROPELLER
Shipbuilder and Marine Engine Builder, June 1953 732

A STABLE NUMERICAL SOLUTION FOR TRANSIENT HEAT FLOW
GEORGE LEPPERT 741

THE INFLUENCE OF SULPHURIC ACID UPON THE DEW POINT OF COMBUSTION GASES
GEORGE A. FEARN, JR. AND COMMANDER WILLIAM TESSIN, USN 753

LOW-HYDROGEN WELDING RODS
The Welding Journal, June 1953 764

THE ORIGIN OF ENGINEERING DUTY ONLY
CAPTAIN R. E. BASSLER, CEC, USN (Ret) 771

REVIEW OF INTERESTING PATENTS ON QUIETING REDUCTION GEARS
JOHN W. SAWYER 791

PAGE

METHOD FOR RECORDING ROUGHNESS OF SUBMERGED SURFACES
JOHN W. SAWYER 816

COMMENTS ON "REPLICAS OF SUBMERGED SURFACES"
JOHN W. SAWYER 821

REGULATORS FOR THE MARINE INDUSTRY
Westinghouse Engineer, July 1953 822

LARGE DRY DOCKS
Engineering, 15 May 1953 832

THE CALCULATION OF NON-LUMINOUS RADIATION IN CONVECTION TUBE BANKS
IRVING GRANET 839

BOILER-WATER TREATMENT TO PREVENT CORROSION
Engineering, 8 May 1953 845

HOW TO CONTROL MARINE CORROSION WITH GALVANIC ANODES
Marine Engineering, June 1953 856

THE DIFFRACTION GRATING AS APPLIED TO THE HARNESSING OF WAVE ENERGY FROM THE SEA
LIEUTENANT J. R. GOODYKOONTZ, USNR 865

BALANCING TURBINE-GENERATOR ROTORS
General Electric Review, July 1953 868

DISCUSSION OF "ACCENT ON ACCESS—THE 'INS' AND 'OUTS' OF MACHINERY SPACES"
JOHN R. WRIGHT 875

DISCUSSION—THE PHENOMENON OF STATIC ELECTRICITY
LOREN G. MAXWELL, Electrical Engineer 876

DISCUSSION BY J. BARRAJA-FRAUENFELDER OF WORSHIP OF THE BMEP AND THE NEW MAN ENGINE 878

BOOK REVIEW
Metadyne Statistics, JOSEPH MAXIMUM PESTARINI 881

DEPARTMENTS

DEATHS 882
NEW MEMBERS 883
ASSOCIATION NOTES 885

Editor: Captain J. E. HAMILTON, U.S.N., Ret.
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INDEX TO ADVERTISERS

Name	Manufacturers of or dealers in	Post office address.	Page
A			
Allis-Chalmers Mfg. Co.	Ship Propulsion and other Equipment for Marine Use	Milwaukee, Wis.	xx
American Brass Co.	Engineering Service on Anaconda Metals	Waterbury, Conn.	xviii
American Chemical Paint Co.	Rust Proofing Chemicals	Ambler, Pa.	xiii
B			
Babock & Wilcox Co.	Marine Water-Tube Boilers, Superheaters Airheaters, Economizers, Oil Burners, Refractories, Seamless and Welded Tubing	Room 665, 161 East 42nd St., New York 17, N.Y.	xiv
Bath Iron Works	Shipbuilders and Engineers	Bath, Me.	xxx
Bethlehem Steel Co.: Shipbuilding Division	Steam Turbines, Marine Boilers, Oil Burning Equipment, Shipbuilders and Repairers	25 Broadway, New York, N. Y.	xxvi
C			
Cleveland Diesel Engine Division, General Motors Corp.	Diesel Engines	Cleveland, Ohio	xvii
Collins Radio Company	Designers and manufacturers of radio communication and navigation equipment for the Armed Services	Cedar Rapids, Iowa	viii
Cooper-Bessemer Corp., The	Marine Diesel Engines	25 West 43rd St., New York City	iii
Combustion Engineering Co.	Marine Steam Generators, Bent Tube and Straight Tube Boilers, Forced-Circulation Boilers, Superheaters, Economizers and Air Heaters	200 Madison, Ave., New York, N. Y.	i
Crane Co.	Crane Valves	836 S. Michigan Ave., Chicago, Ill.	ii
Cutler-Hammer, Inc.	Electric Control Apparatus	1354 St. Paul Ave., Milwaukee, Wis.	viii
D			
De Laval Steam Turbine Co.	Steam Turbines	485 Nottingham Way, Trenton, N. J.	x
E			
Electric Boat Co.	Better Submarines for Greater Security	445 Park Avenue, New York 22, N. Y.	xxix
Electric Storage Battery Co.	Exide Batteries	Allegheny Ave. and 19th St., Philadelphia, Pa.	viii
Elliott Co.	Elliott Motors, Generators, Steam and Gas Turbines, Condensers, Deaerating Feedwater Heaters, Turbo Chargers, Strainers, Tube Cleaners, etc.	Jeanette, Pa.	iv

Name.	Manufacturers of or dealers in	Post office address.	Page
F			
Fairchild Engine & Airplane Corporation (Aircraft Division)	Flying Box Cars	Hagerstown, Md.	xxiv
Farrel-Birmingham Co., Inc.	Precision Gears	Ansonia, Connecticut	xii
Foster Wheeler Corp.	Marine Steam Generators, Condensers, Bent Tube and Straight Tube Boilers, Superheaters, Water Walls, Economizers, Air Heaters, Feed Water Heaters, Evaporators, Condenser Tubes, Pumps, Waste Heat Boilers, Vacuum Refrigeration Systems	165 Broadway, New York 6, N. Y.	xi
G			
General Electric	Electric Machinery of All Classes	Schenectady, N. Y.	xxiii
Gibbs & Cox, Inc.	Naval Architects and Engineers	New York, N. Y.	vi
Griscom-Russell Co.	Distilling Plants, Feed Water Heaters	285 Madison Ave., New York	vi
I			
International Nickel Co.	Producers of Nickel	67 Wall St., New York, N. Y.	v
International Telephone and Telegraph Corp.	Communications — Research — Manufacturing	67 Broad St., New York, N. Y.	xxvii
J			
Johns-Manville	Insulation, Refractory Cements, Packings, Brake Linings, Asbestos Ebony for Switch and Panel Boards, Waterproofing Transite Asbestos Sheets, Transite Pipe, Roofing and Shingles, Flooring, Insulating Board Products	22 East 40th St., New York City	viii
K			
Kingsbury Machine Works, Inc.	Thrust Bearings, Journal Bearings, Thrust Meters	Frankford, Philadelphia, Pa.	xxi
L			
Lanman Engraving Co.	Photo Engravers	612 L St., N. W., Washington, D. C.	iv
Lidgerwood Industries, Inc.	Steering and Deck Machinery	7 Dey Street, N.Y.7,N.Y.	xix
M			
Moffitt, Lucian Q., Inc.	Cutless Bearings for Stern Tubes and Struts	Akron, Ohio	iii
N			
Newport News Shipbuilding & Drydock Co.	Naval and Merchant Vessels	Newport News, Va.	ix

Name	Manufacturers of or dealers in	Post office address.	Page
R			
Radio Corporation of America: Govt. Equip. Section	Radio Equipment	Camden, N. J.	xviii
Raytheon Mfg. Co.	Contractors to the Armed Services	Waltham 54, Mass.	xv
S			
Selby, Battersby & Co.	Deck Covering for Ships	5220 Whitby Avenue, Philadelphia 43, Pa.	xxi
Sperry Gyroscope Co., Inc.	Radar, Loran, Gyro-Pilots, Gyro-Compasses, Electric and Hydraulic Steering Equipments, Magnetic Compass Pilot, Rudder Angle Indicator, Naval Fire Control Instruments, Aircraft Gyropilots, Flight Instruments	Great Neck, N. Y.	vii
T			
Terry Steam Turbine Co.	Steam Turbines	Hartford, Conn.	xxviii
U			
U. S. Naval Institute	U. S. Naval Institute Proceedings	Annapolis, Md.	xxv
W			
Ward Leonard Electric Co.	Electric Control Devices	Mount Vernon, New York	xxviii
Westinghouse Electric & Mfg. Co.	Marine Steam and Electrical Equipment	East Pittsburgh, Pa.	xvi
Worthington Pump & Machinery Corp.	Pumps, Condensing Apparatus, Diesel Oil Engines, Gas Engines, Fluid Meters, Compressors, Feed Water Heaters	Harrison, N. J.	xxii

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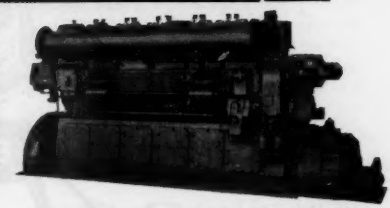

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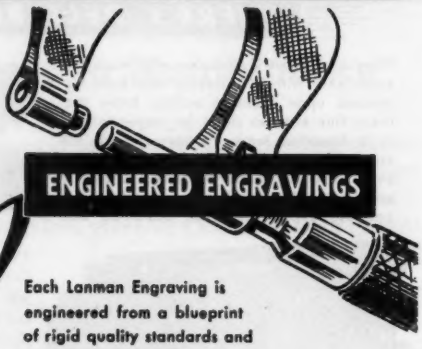

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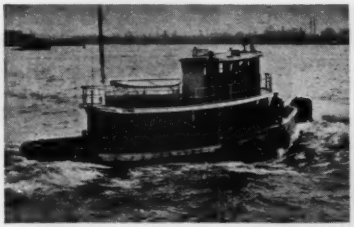

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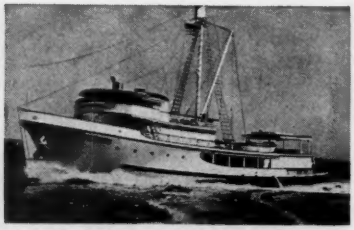

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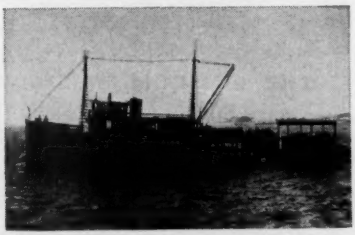

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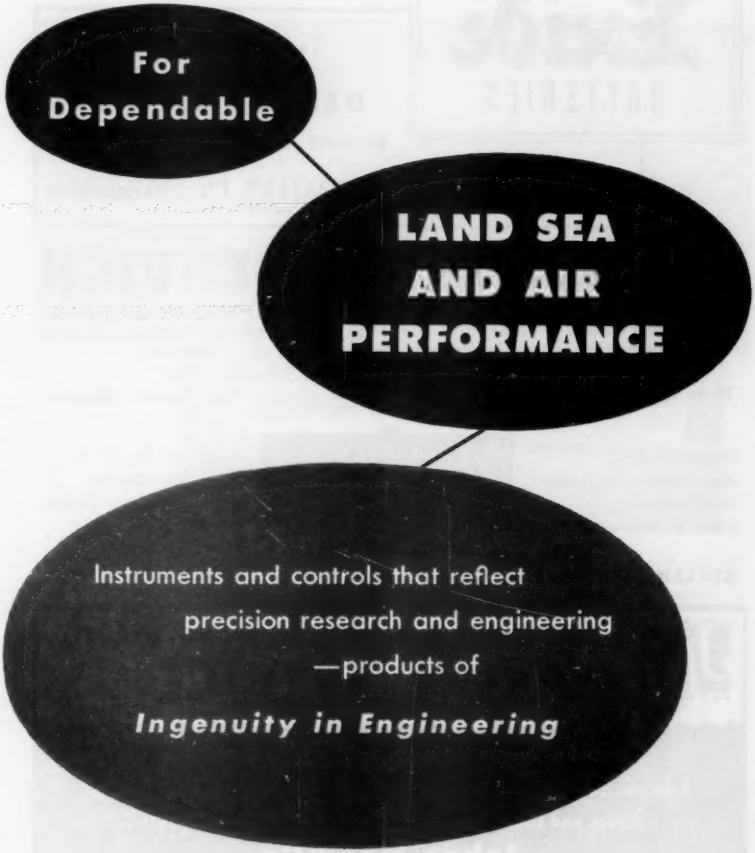

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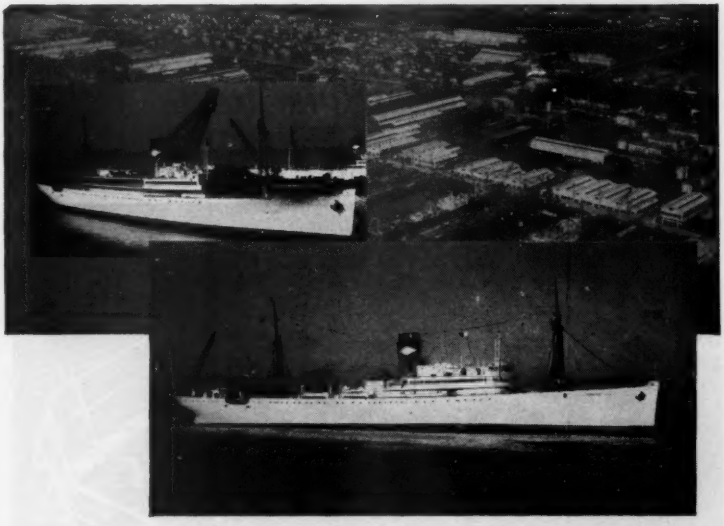

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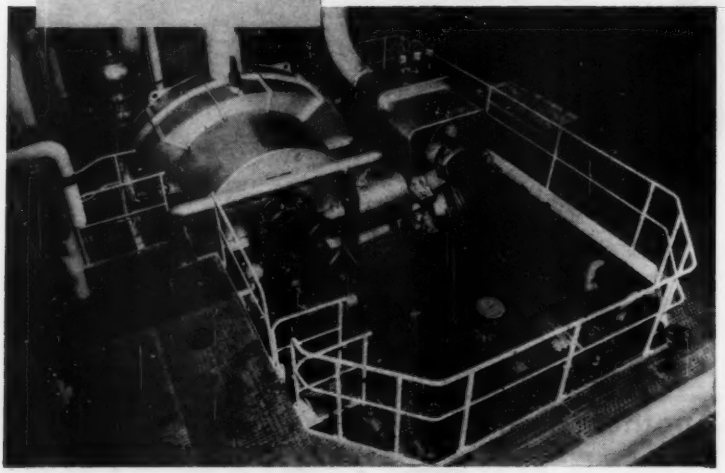

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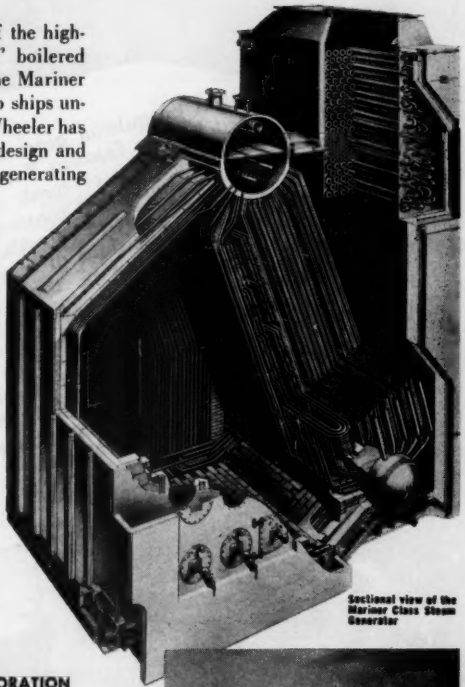

Sectional view of the Mariner Class Steam Generator

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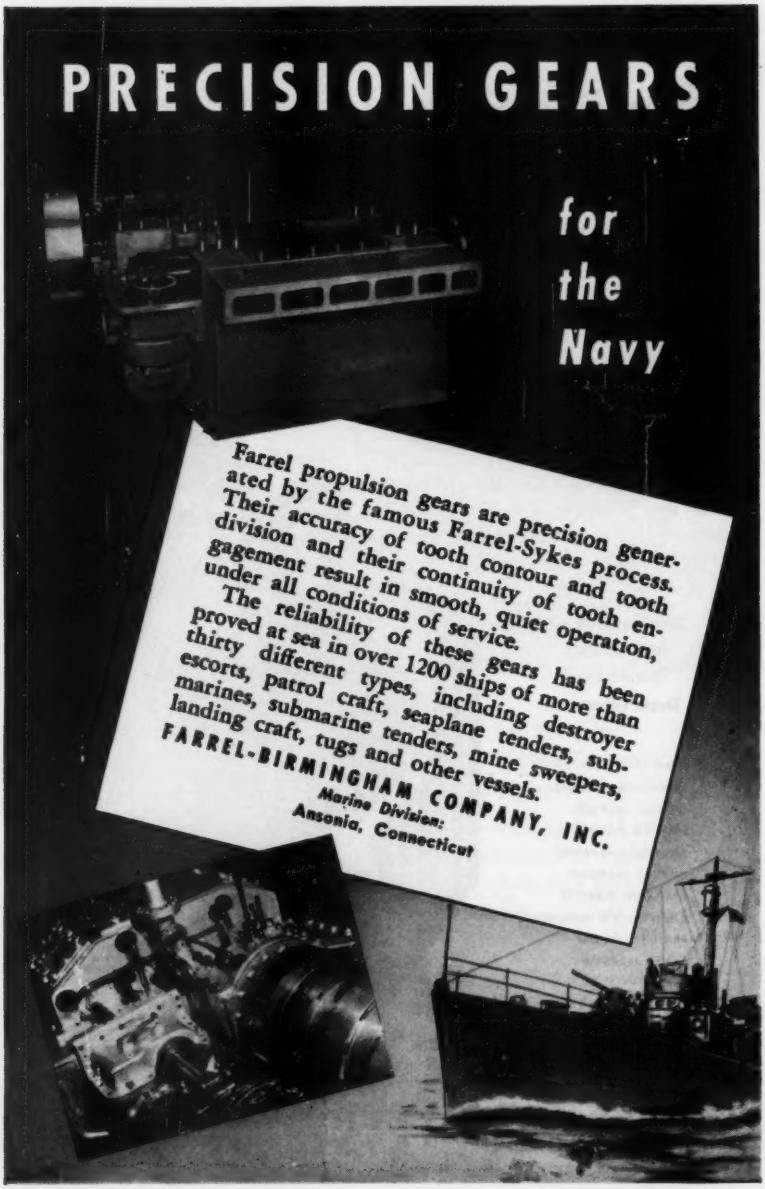
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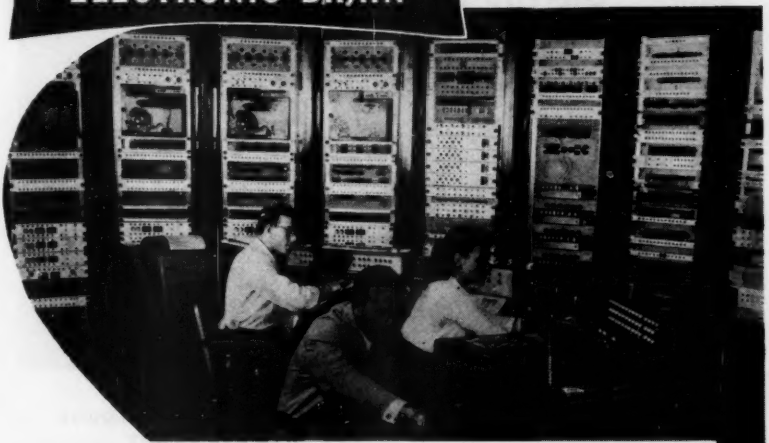
M-323

IT TAKES MANY MINDS TO MAKE AN "ELECTRONIC BRAIN"

RAYTHEON AUTOMATIC DIGITAL COMPUTER developed for the Office of Naval Research and used at the Naval Air Missile Test Center, Point Mugu, California.



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Few companies are equipped with the diversity of talent, the technical background or the production facilities necessary to venture into this extremely complex field. Raytheon is unique in having under its many roofs not only the kind of people but the products and production facilities required to bring analog and digital computers into practical being.

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Westinghouse MARINE SERVICE

ERRATUM

JOURNAL FOR AUGUST, 1953, VOL. 65, No. 3.

In the article "A Relationship for Preliminary Propeller Diameter" on page 546 the ratio $\frac{\delta}{B_p^{0.6}}$ occurs four times. In each place it should be $\frac{\delta}{B_p^{0.4}}$. The final results are not affected by this error.

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JOURNAL

OF

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

VOL. 65. NOVEMBER 1953. No. 4

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The Society as a body is not responsible for statements made by individual members

COUNCIL OF THE SOCIETY

(Under whose supervision this number is published).

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MR. H. E. CARLETON — Captain W. L. PRYOR, U. S. N.

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MR. J. J. KENNEDY

Captain J. E. HAMILTON, U.S.N., (Ret), Secretary-Treasurer

SECRETARY'S NOTES

THE ANNUAL MEETING

Election for 1954

The Annual Meeting of the Society was held in Washington on Tuesday, 6 October, 1953.

The following report of the nominating committee of which Rear Admiral Harvey F. Johnson, U.S.C.G. Ret., was chairman was submitted to and accepted without change by the membership:

6 October, 1953

"The American Society of Naval Engineers, Inc.
Washington, D. C.

Gentlemen:

The committee, of which the undersigned is Chairman, and of which Captain C. G. Grimes, U.S.N., Captain R. E. W. Harrison, U.S.N.R., Mr. Warren T. Johnson and Mr. H. E. Carlton are the other members, appointed by Rear Admiral E. W. Sylvester, U.S.N., President, in accordance with Section 23 of the By-Laws, by his letter of September 4, 1953, to present nominations for offices of the Society at its Annual Meeting on 6 October, 1953, presents the following nominations:

For President

Rear Admiral E. W. Sylvester, U.S.N.

For Secretary-Treasurer

Captain J. E. Hamilton, U.S.N., Ret.
Captain W. R. Millis, U.S.N., Ret.

For Member of Council

Regular Navy Officers

Captain F. R. Furth, U.S.N.
Captain H. M. Heiser, U.S.N.
Captain L. V. Honsinger, U.S.N.
Captain Hugh Webster, U.S.N.

Coast Guard Officer

Commander J. W. Naab, U.S.C.G.
Commander C. E. Columbus, U.S.C.G.

Naval Reserve Officers

Commander C. H. Campbell, U.S.N.R.
Commander John Sawyer, U.S.N.R.

Civilian Member

Mr. J. F. Hanlon, Westinghouse Electric Corporation
Mr. F. J. Lindauer, Fairbanks, Morse and Company

Respectfully submitted,

Harvey F. Johnson, Rear Admiral, U.S.C.G., Ret.
Chairman"

Ballots have been mailed to all members for return prior to 26 December, 1953.

Society Finances

A verbal report on the subject of Society Finances was made by the Secretary-Treasurer. This was based largely on a report which was submitted by a sub-committee of the council. This sub-committee consisted of Rear Admiral R. E. McShane, U.S.N., chairman, and Captain C. G. Grimes, U.S.N., and Captain P. W. Snyder, U.S.N., as members.

The sub-committee studied those matters which were set forth briefly in the Secretary's note in the August 1952 issue of the JOURNAL.

As a result of this report the following decisions were reached by the Council:

a. Retain the present assets of the Society as a reserve for emergencies and operate within income.

b. Continue the JOURNAL at essentially its present size and scope. This as interpreted by the Editor means from 900 to 1,000 pages per year containing the best original or reprint material which is obtainable.

c. Keep annual dues at $7.50.

d. Increase *foreign* subscription rates to $20.00 per year.

e. Make every effort to increase membership. With a potential of several hundred thousand eligible members this should be possible if the proper way to reach prospects can be worked out.

f. Continue the present office arrangement.

g. Continue the present size of staff with particular encouragement to Mr. A. G. Fessenden to remain as Clerk.

The members present at the annual meeting accepted these decisions of the Council without comment.

CHANGES IN OFFICERS

Upon detachment from duty in Washington, as Chief of the Bureau of Ships, Rear Admiral Homer N. Wallin, U.S.N., resigned as President of the Society. The Council appointed Rear Admiral E. W. Sylvester, U.S.N., to succeed Admiral Wallin on 1 August for the remainder of 1953. This action left a vacancy on the Council which was filled by the appointment of Captain W. L. Pryor, U.S.N. Shortly afterward, Captain Pryor was unexpectedly transferred from Washington to Yokosuka, Japan, again creating a vacancy. This was filled by the appointment of Captain G. M. Chambers, U.S.N. Captain Chambers' term will expire on 31 December, 1954.

MEMBERSHIP

On 1 January, 1953 the membership of the Society was:

Naval members	1,396
Civil members	933
Associate members	396
Total	2,725

There had been 283 new members with 35 resignations and 17 deaths up to 6 October giving a net membership of 2,956 on that date. There are 136 members who will be dropped on 1 January, 1954 if they have not adjusted their accounts by that time. Thus the prospect is for a net increase of about 100 for 1953.

ANOTHER MEMBER RECEIVES RECOGNITION

William Francis Gibbs Receives Franklin Medal

At the annual "Medal Day" meeting of the Franklin Institute in October, Mr. William Francis Gibbs was awarded the Institute's Franklin Medal, "because he has labored successfully for forty years to bring the best of engineering and architecture into shipbuilding, culminating in the construction of the record-breaking S.S. *United States*."

The Franklin Medal, founded in 1914 by Samuel Insull, is awarded annually to those workers in physical science and technology, without regard to country, whose efforts, in the opinion of the Franklin Institute, have done most to advance a knowledge of physical science or its application.

Mr. Gibbs is President of Gibbs & Cox, Inc., and has been a member of the Society since 1938.

RESEARCH BY THE FEDERAL GOVERNMENT

NATIONAL SCIENCE FOUNDATION REPORTS ESTIMATES OF FEDERAL OBLIGATIONS AND EXPENDITURES FOR SCIENTIFIC RESEARCH AND DEVELOPMENT FOR FISCAL YEAR 1954

Both obligations and expenditures of Federal agencies for scientific research and development are expected to drop in fiscal year 1954 from the record totals established in previous years, according to the latest estimates compiled by the National Science Foundation.

Estimates of obligations for research and development are $2,074 million for 1954 compared to $2,187 million for 1953;

expenditures are estimated at $2,187 million in 1954 and $2,205 million in 1953. Since the lag between obligations and expenditures has averaged about 9 months over the past several years, the decline in obligations for 1954 will presumably be reflected in a further decrease in expenditures in fiscal 1955.

These estimates, revised as of August 24, 1953, were based on appropriations approved by the 83d Congress, 1st Session. These 1954 estimates are still tentative since several agencies plan further revisions in their programs.

The Department of Defense estimates constitute the largest portion of the totals for both obligations and expenditures. Present figures indicate that in fiscal year 1954 the Department may obligate $1,556 million, including a carry-over of $142 million from previous years.

The total obligations and expenditures for the major agencies for fiscal 1952, 1953, and 1954 are summarized in the table on the next page. The trend of research and development obligations and expenditures for the period 1948 through 1954 is shown on the attached chart.

This information was compiled by the Foundation in connection with its continuing studies of the research and development activities of the Federal Government. These reports will be of considerable value to many Federal and private groups concerned in the administration and planning of Federal research and development programs.

SOURCES OF SHIPPING STATISTICS

Volume 9, No. 2 of Shipping Survey, published by the Association of American Ship Owners carried the following article which will be of interest to some of our members:

Students of maritime affairs have often had difficulty finding usable statistics that might throw light on various problems of the American merchant marine. Numerous encounters with complicated and often noncomparable reports issued by various Government agencies have consequently led to an analysis of what shipping statistics are available for the period since World War I.

The tabulation of "Sources of Shipping Statistics" contained in this study is the end result of that analysis. It lists in very condensed form the main reports available to the economist,

SUMMARY TABLE OF OBLIGATIONS AND EXPENDITURES OF FEDERAL AGENCIES FOR SCIENTIFIC RESEARCH AND DEVELOPMENT IN FISCAL YEARS 1952, 1953, AND 1954

(Millions of dollars)

Revised: August 24, 1953

Agency	*Obligations*			*Expenditures*		
	F. Y. 1952	*F. Y. 1953*	*F. Y. 1954 (Estimate)*	*F. Y. 1952*	*F. Y. 1953*	*F. Y. 1954 (Estimate)*
Department of Defense.....	1,705	1,650	1,556	1,315	1,646	1,636
Atomic Energy Commission.	229	247	239	250	260	266
National Advisory Committee for Aeronautics.....	82	79	73	67	79	88
Department of Agriculture..	56	57	68	57	58	63
Department of Health, Education and Welfare.....	53	67	63	65	74	61
Department of the Interior..	36	36	32	33	37	33
Department of Commerce..	31	23	17	28	24	17
Other Agencies.....	25	28	26	24	26	24
Total, all agencies.....	2,217	2,187	2,074	1,839	2,205	2,187

NOTE: Column items may not add to totals because of rounding.
SOURCE: National Science Foundation.

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the student researcher or the layman seeking basic data. It is divided into two groups: reports no longer published and those currently available.

The analysis served to emphasize such matters as the inadequacy of reports on water-borne foreign commerce in the past, the long delays between collection of the statistics and their publication (sometimes three years or more), and the present difficulty confronting anyone seeking comparable figures over a period of years, or even currently, on the flow of specific commodities between specific U.S. and foreign ports. A brief review of available shipping statistics should be helpful to researchers in using the tabulation.

Pre-World War II Period

There were three main sources of shipping statistics during the nineteen twenties and thirties: the Department of Commerce, U.S. Army Engineers and the U.S. Shipping Board, later the U.S. Maritime Commission and now the Maritime Administration.

Main report of the Commerce Department was its "*Foreign Commerce and Navigation of the United States*," an annual report begun in 1923 when the New York Section of Customs Statistics was transferred from Treasury to Commerce. Data collected also was published monthly under the title "*Monthly Summary of the Foreign Commerce of the United States*." Figures usually were at least 18 months old by the time the annual report was published and in one case, the final volume for 1945 and 1946 was not published until 1950.

Although an essential source for statistics during the 1923–46 period, the Commerce report was inadequate in many respects. The Commerce report was based, as are present Government reports, on customs declarations on all shipments over $100, of which there currently are about 10 million per year. All of these were reported by Commerce prior to 1946 with no data as to means of transport. However, only about 50 per cent of them by number (78 per cent by weight and 79 per cent by value) moved by vessel, the rest being carried by railroads, airplanes, trucks or other means. In addition, while the Commerce report provided considerable detail on commodities, detail on countries of origin and destination were reported in other tables. The three essential items of information for shipping—port of origin, port of destination, and commodity—were nowhere brought together in one table. Also, volume of commodities was not expressed in shipping weight but in usual units of sale: bushels, gallons, yards or other units, which are often difficult to convert to shipping weight.

The Commerce publication was discontinued after the 1946 volume.

Second important source of shipping statistics for the 1920–40 period, and even today, is the annual reports of the Chief of Army Engineers. Part 2 of the report, titled "*Commercial Statistics*" assumed its present form in 1920, by which time the Army Engineers had been authorized to collect statistics on all water-borne commerce for each U.S. port or waterway. Prior to 1920, the Board of Engineers and Harbors of the War Department had collected and published some statistics.

These reports list U.S. exports and imports by commodities in terms of short tons. The reports do not include data as to port of origin or port of destination. Prior to 1947, statistics given were based on special statements by shipowners to the Army Engineers, but now they are based on Census punch card reports which in turn are based on a more detailed customs declaration.

U.S. Shipping Board and Successors

The U.S. Shipping Board, created in 1916, inaugurated in the early 1920's the most useful series of reports, so far as the maritime industry is concerned, published up to that time, and these were continued by its successor, the former U.S. Maritime Commission, until 1940. One of them, a quarterly report showing employment of all U.S. flag vessels over 1,000 gross tons, still is published by the present Maritime Administration in the Commerce Department.

Main commodity reports published by the Shipping Board were Nos. 42 and 275 and No. 2610, the latter a consolidation of the first two after they were discontinued. These reports were based on ships' manifests and their general content is described in the tabulation. Weight of commodities was given in long tons and included containers, important to the shipowner. The reports did not separate dry-cargo and tanker cargo, but summary reports issued annually did so. Main weakness of these reports was that some were on fiscal and some on calendar year bases, and comparability has presented problems. These reports were discontinued after 1940.

FOREIGN TRADE REPORTS NO LONGER PUBLISHED

No. and Title	*Dates*	*Published by*	*Description*
Foreign Commerce and Navigation of the United States.	1923 thru 1946	Dept. of Commerce annually, monthly summaries	Shows total imports and exports of U.S. by customs districts, by value, but not by weight. No separation of vessel from other shipments and no data on ports of origin or destination.
No. 42—Volume of Water-Borne Commerce of the U.S. by Ports of Origin and Destination.	1923 thru 1937 fiscal years	U.S. Shipping Board and Maritime Commission	Shows total vessel imports and exports by U.S. by port of origin and port of destination, by 12 or 14 main commodities per port with rest grouped under miscellaneous. Weight in long tons.

No. and Title	*Dates*	*Published by*	*Description*
No. 275—Imports and Exports of Commodities of U.S. Coastal Districts and Foreign Trade Regions.	1926 thru 1937 Calendar and fiscal year except 1936-37 only Calendar	U.S. Shipping Board and Maritime Commission	Shows flow of 60 to 80 commodities from five U.S. Coastal Districts (North Atlantic, South Atlantic, Gulf, Pacific, and Great Lakes) to and from 20 foreign trade regions. In 1936-37 published under title: "Water-Borne Foreign Commerce of the United States."
No. 2610—Water-Borne Foreign and Non-Contiguous Commerce and Passenger Traffic of the United States.	1938 thru 1940	U.S. Maritime Commission	This report consolidated statistics in Nos. 42, 275 and 157, which dealt with passenger traffic. It gives less port detail, but shows percentage carried by U.S. flag vessels.

Revised Postwar Statistical Program

Steps were begun in 1941 to coordinate the collection and dissemination of shipping statistics by the Government, and in 1942, upon passage of the Federal Reports Act of 1942, the Bureau of the Budget assumed direction of the task of coordination. The job, although begun prior to World War II, was not fully completed until 1947, when the Census Bureau of the Department of Commerce assumed sole responsibility for collection of the statistics.

Basis of all current statistics are import entry forms and shippers' export declarations. Information not included in these reports prior to the war now is included such as details on weight of shipment, port of lading and unlading, flag of vessel, and type of carrier.

All of the information is punched on machine tabulation cards (one for each shipment) by the Census Bureau. The Bureau then uses one set of these cards to compile its own reports and furnishes one set each to the Army Engineers and the Maritime Administration. The Army Engineers use the cards to compile figures for their annual report. The Maritime Administration no longer publishes any reports on shipping volume and movement but uses its set of cards to prepare special staff studies from time to time.

Bureau of Census Reports

The most useful current reports are those of the Census Bureau, the most important of which are described in some detail in the Table. The Census reports fall into two groups: the FT reports, which are published monthly, with annual recapitulations, and the SM reports, which though compiled monthly, are not published. Copies are available, however, at designated Commerce Department field offices.

The FT reports provide a reasonably good over-all view of U.S. foreign trade, giving value, weight (in millions of pounds), U.S. port of lading or unlading, and foreign trade area of origin or destination. They are deficient in that there is no specific detail on commodities and the foreign port information is by region rather than port.

FOREIGN TRADE REPORTS CURRENTLY PUBLISHED OR AVAILABLE

No. and Title	*Year Initiated*	*Prepared by*	*Available After*	*Description*
Commercial Statistics—Part 2, Annual Report: Chief of Army Engineers.	1920 annual	U.S. Army Engineers	6 to 18 months	Shows in short tons weight of commodities moving by vessel in and out of U.S. ports. Originally based on reports by vessel owners, now on Census figures. No data on ports of origin or destination.
Employment of U.S. Flag Merchant Vessels; 1,000 Gross Tons and Over.	1922 quarterly	Maritime Administration in Commerce Dept.—formerly U.S. Shipping Board and Maritime Commission	30 to 60 days	Shows current employment of all U.S. flag vessels by type and trade, with privately owned and Government-owned separated.

FOREIGN TRADE REPORTS REGULARLY PUBLISHED BY CENSUS BUREAU

Number and Title	*Initiated*	*Available After*	*Description*
FT 972—United States Foreign Water-Borne Trade by United States Port.	1946 monthly and annual	100 days or more	Table 1 shows U. S. exports and Table 2 general imports carried by commercial vessel in terms of shipping weight and dollar value for the various customs districts and approximately 120 United States ports by type of service (dry cargo vessel and tanker). Table 3, added in August, 1950, shows consolidated figures for total United States foreign water-borne trade, including commercial exports (Table 1), commercial imports (Table 2), in-transit shipments (FT 981), and Department of Defense controlled cargo (FT 976).
FT 973—United States Foreign Water-Borne Trade by Trade Area.	1946 annual, thereafter monthly and annual	100 days or more	These reports give U. S. imports and exports in terms of shipping weight (but not value) to and from each of 20 foreign trade areas. Percentages of dry-cargo shipments on U. S. flag vessels are shown for both liner and tramp. Comparable detail on tanker tonnage is given in separate tables.
FT 976—Department of Defense Controlled Cargo Exported by Vessel under the United States Foreign Aid Programs, and "Special Category" Non-Department of Defense Controlled Cargo Exported by Vessel.	1948 title and coverage altered 1949	100 days or more	Beginning in 1948, information on export shipments under such special foreign aid programs as Civilian Supply, Greek-Turkish Aid, Economic Cooperation Administration, etc., were tabulated in FT 976, then entitled *Participation of Army and Navy Operated Vessels (American Flag) in Shipments under the United States Foreign Relief Program.* The cargoes consist of exports from the United States on United States flag vessels such as Army or Navy transports and commercial vessels chartered by the Department of Defense under time charter, voyage charter, and space charter arrangements.

Number and Title	*Initiated*	*Available After*	*Description*
FT 981—Shipping Weight and Dollar Value of Merchandise Laden on and Unladen from Vessels at United States Ports during In-transit Movement of Merchandise from One Foreign Country to Another.	1946, issued monthly 1948 on	100 days or more	Statistics for in-transit cargo in the following terms for both inbound and outbound traffic: total, dry cargo vessel, and tanker, for various U. S. customs districts and approximately 28 important ports. These in-transit shipments are omitted from the vessel shipping statistics shown in Tables 1 and 2 of FT 972 (but included in Table 3), FT 973, FT 976, and SM 303.
FT 1000—United States Water-Borne Foreigh Trade: Foreign Trade Area by United States Coastal District.	1953	100 days or more	This report was designed to supplement FT 973. It provides information on the shipping weight of United States imports and exports by five United States coastal districts and by foreign trading area. The report deals with dry cargo only, classified as "liner" or "irregular service" vessels. Information is included on the flag of the vessels.

The commodity detail can be obtained from the SM reports, that are recorded on machine tabulated code sheets. But the commodities are designated in code, so that a code schedule is essential to use them. Probably also essential for the casual user is considerable study of "*Foreign Trade Statistical Notes*," a monthly publication of the Bureau which provides much explanatory material of value in using its various reports.

In addition to its regular FT and SM reports, the Census Bureau publishes special studies from time to time, usually announced beforehand in the "*Notes*," and will also undertake special studies for private concerns willing to pay the cost. Shipping companies or organizations also may purchase duplicate sets of the Census machine punch cards for certain ports or trade areas in which they may be interested.

Shipping statistics being collected and made available today are on the whole adequate, but their compilation and dissemination still leave much to be desired. This contrasts sharply with the situation that existed in the past and in this connection it is interesting to note that when legislation designed to give effect to American maritime policy was under consideration, basic economic data that should have been at hand was either not available at all or was so old that its value was questionable.

Most essential current facts are now available at one place or another in Government but, unfortunately, some of them have to be dug out of complicated (for the layman) machine tabulation sheets which are in code and which must be decoded to be intelligible and useful. Information thus obtained still must be correlated with other figures found in published reports in order to trace historical changes in the direction and volume of trade. It would be of great value if the essential facts concerning the movement of economically important commodities between specific U.S. ports and specific foreign ports, by weight and value and by type and flag of carrier could be included in a single report to which both the industry and interested Government agencies could refer for reliable and comparable statistics.

UNPUBLISHED, MACHINE TABULATED, MONTHLY FOREIGN TRADE REPORTS BY CENSUS BUREAU

(These were initiated in 1946 and no annual summaries are made)

Number and Title	*Date Available*	*Description*
SM 303—United States General Imports of Merchandise on Vessels by Type of Vessel, by Domestic Port of Unlading, by Foreign Port of Lading, by Schedule "T" Commodity.	80 days	This report shows for each United States port the value and shipping weight (pounds) of water-borne imports by foreign port of lading. Imports are shown for each of the 162 commodities or commodity groupings listed in Schedule T. Imports on liner (dry cargo) vessels, irregular or tramp (dry cargo) vessels and tanker vessels are shown separately.
SM 703—United States Exports of Domestic and Foreign Merchandise, by Schedule "S" Commodity.	100 days	This report presents detail on United States exports comparable to that given in SM 303 for imports. Schedule S includes 187 commodities or commodity groupings.
SM 353—Inbound Vessel Shipments of In-Transit Merchandise by Type of Vessel, by Domestic Port of Unlading, by Foreign Port of Lading, by Schedule "T" Commodity.	80 days	Inbound in-transit shipments are shown for each United States port in terms of dollar value and shipping weight. These shipments are comprised of merchandise arriving by vessel from a foreign country and shipped through the United States to another foreign country without being entered as an import. Detail is given on type of carrier, as in SM 303 and SM 703.
SM 753—Outbound Vessel Shipments of In-Transit Merchandise, by Schedule "S" Commodity.	100 days	This report presents detail on United States outbound in-transit shipments comparable to the inbound data included in SM 353.

Number and Title	*Date Available*	*Description*
SM 313—United States General Imports of Merchandise on Vessels by Country of Origin, by Schedule "T" Commodity, by United States Customs District of Unlading.	100 days	This report shows the value and shipping weight of imports on all vessels, and the shipping weight only of imports on United States flag vessels, from individual countries of origin by shipping commodity group and by customs district of unlading.
SM 713—United States Vessel Exports of Domestic and Foreign Merchandise by United States Customs District of Lading, by Country of Destination, by Schedule "S" Commodity.	100 days	United States exports, in terms of value and shipping weight, are given for each United States customs district by country of destination and shipping commodity group.
SM 352—United States General Imports of Merchandise on Vessels by Type of Vessel, by Domestic Port of Unlading, by Foreign Port of Lading, by Schedule "T" Commodity, by Country of Origin.	80 days	These two reports are identical in coverage and similar in arrangement to SM 303 and SM 703, except that they include information on country of origin or destination, a type of information not given in SM 303 and SM 703.
SM 752—United States Exports of Domestic and Foreign Merchandise on Vessels by Type of Vessel, by Domestic Port of Lading, by Foreign Port of Unlading, by Scheduld "S" Commodity, by Country of Destination.	100 days	

NOTE—All commodity information in the SM Census reports is in code, and copies of the codes are available with the reports. The Schedule "S" is a list of 187 commodities and commodity groupings for exports and Schedule "T" is a similar list of 162 commodities or commodity groupings for imports. Both are condensations of much more detailed listings required by Customs. SM reports are available in the following Commerce Department field offices: Room 2023, Federal Office Building 3, Washington 25, D. C.; Room 434, Custom House, New York 4, N. Y.; Room 1111, Masonic Temple Building, 333 St. Charles Avenue, New Orleans 12, La.; and Room 315, Flood Building, 870 Market Street, San Francisco 2, Calif.

TECHNOLOGY OF THE FIFTH WHEEL

CAPTAIN R. E. W. HARRISON, USNR

THE AUTHOR

was born in Manchester, England, in 1893. Educated Manchester College of Technology. With Royal Engineers, British Army 1914-1919, Egypt, Gallipoli, Sinai, France, Belgium. Industrial Engineering experience includes special apprenticeship and supervisory positions with Churchill Machine Tool Company, England, in the building, design and engineering selling of precision grinding machinery; in 1926 as Director of Engineering, Cincinnati Grinders, Cincinnati Milling Machine Company; 1934 Chief, Machinery Division, U. S. Department of Commerce; 1935 Vice-President Chambersburg Engineering Company; in War II, on staff of Assistant Secretary U. S. Navy, and later as Special Assistant to the Under-Secretary. Registered Mechanical Engineer in Ohio, New York, Pennsylvania, Maryland and District of Columbia. Fellow, ASME and Royal Society of Arts; Member other Engineering Societies in USA and Europe. Present Duty, Industrial Engineer, Field Activities, BuShips.

PREMISE

So many mechanisms in use today embody the principle and practice of the fifth wheel, that exploration of its genesis—its use—and the results thereof seem well justified.

DISCUSSION

Invention of the wheel principle marked a major advance in civilization in more ways than one. Its age is such that the date of origin is lost in the mists of antiquity; however, as a first—or primary—move in the reduction of backbreaking labor, the humble wheelbarrow could and should be enshrined and revered on a par with the accolades bestowed on the motor car and the indoor toilet. Two wheels were, thereafter, a natural, and the handcart, while registering another major advance, was not so epochal as the wheelbarrow; the bicycle also was a boon of great value—after we learned how to make it and then to ride it.

Three wheels: The virtues of the 3-point bearing are well known to all mechanics and engineers, probably the best example of practicality in use today is the three-point wheel support built into a modern airplane. There is a never-ending source of wonderment to the uninitiated in the way in which a 25-ton or more airplane can be landed on three wheels and, thereafter, maintained in a state of maneuverability on these same wheels on the ground.

Four wheels: Four-wheel vehicles today are about the most common-place object on the roads, and although an elaborate system of spring suspension is necessary to keep all four in more or less even contact pressure with the ground, there is plenty of proof that the mechanism works satisfactorily. Properly engineered, the four-wheel vehicle is a stable, practical piece of equipment, capable of operating continuously under the most arduous conditions. Probably the best active demonstration today of the feasibility of the age in which we live is exemplified by the universal use of the common automobile.

The Fifth Wheel: Search and research, such as has seldom, hitherto, been practiced, fails to reveal a valid justification for the existence of the fifth wheel. It is a practical impossibility to suspend and spring the wheel in such a way that it can carry any just portion of the load or burden. At best, it is an unsightly excrescence. Despite the most vigorous stretching of a vigorous imagination, all answers turn up zero. There seems, therefore, no mechanical, dynamic, or in fact any justification for a fifth wheel other than the one in the boot of the car which only sees the light of day when a flat tire makes the presence of this additional wheel, ever welcome, or recognized.

From all of the foregoing, therefore, the philosophy of mankind seems well founded in its concept that the fifth wheel is something which toils not, neither does it spin productively; that is, spin in the sense of making something useful. Nevertheless, the fifth wheel is with us—in vast numbers, characterized by reams of superfluous paper, bloated payrolls, delaying procedures, and withall, a becoming self-effacement, but without doubt a notable persistence, which makes a piker out of the lamprey eel.

1. THE BIG COMMITTEE

For instance, what busy executive has not experienced the irk of membership on a big committee; with no time for even fleeting amusement at the antics of the pompous, bungling chairman, with the ill-prepared agenda which starts in the air and finishes in the air without ever getting its feet onto working ground.

Motivation for the acceptance of membership in big committees of the Chamber of Commerce variety, or the various "do good" club type, is hard to attribute to anything other than the herd instinct. In his heart, Mr. Busyman violently objects, but ends up by going along rather than risk the odium bound to go with refusal.

Presumably when the committee is organized there is a job to be done, but it seems that nine-tenths of these futile, time-consuming, group meetings end up with a resolution which could, or could not, contain the elements needed as principles with which to guide the matter under review. The committee, however, dismally falls flat on its collective face when it comes to the task of writing the needed corollary of implementation. Like Calvin Coolidge's parson, who preached a long sermon about sin, Cal, when asked what the discussion amounted to, simply said, "he's agin it". So—heading the list of the fifth wheels which spin not, or which exert no tractive effort, is the big committee, business, social, church, government, or what have you, be the origin. Practically the only committee which registers, is the 3-man job, with one accepted as a quorum, and the other two out of the picture—dead, resigned, or out of town.

2. COPIES FOR EVERYBODY

Second on the list of time consuming fifth wheels is the practice of "copies of everything for everybody". Sheaves of useless paper, taking endless time to read, clerks to file, and files to fill, as well as much needed space to occupy; truly there ought to be a law, or something which prohibits whatever it is, support, or inflation of the ego, acquired by those whose gage of self-importance can only be maintained at a full head of steam by inundating all and sundry with copies of his wretched correspondence.

A functional organization chart, properly keyed in with distribution lists attached will, in any business organization, automatically tell the secretary how many copies to make, and to whom to send them, and this procedure, if adhered to, equally automatically takes a big proportion of her work, and that of the long-suffering colleagues, out of the fifth wheel classification.

3. THE EXECUTIVE ASSISTANT

This bird, who is not nearly so rare as he ought to be, is another type of superfluous wheel, generated by the boss-man who never makes a practice of delegating executive authority, anyway. However, there are those amongst us who will accept and operate in this kind of a billet, going through the make-believe motions which fill in his time until the next pay check rolls around.

Bouncing along the highway of life, through the mud, the rain, the dust and the sunshine, Mr. Executive-Assistant, who does not execute, lives a life of torment if there is anything to him, or more frequently, he folds his hands and lifts his eyes to the clouds, hoping that some day some fortuitous circumstance will entrap his boss in its meshes, to the point where he simply will not be able to do all of everything, and must, therefore, relieve the tedium of his willing, and sometimes able, assistant, by giving him some job to do with the necessary authority to make this small job stick.

Why do we have this type of fifth wheel? Heaven only knows. All he does is fill up a needless oblong on the organization chart, draw down a pay-check which he does not earn, use space, office facilities, and perhaps a secretary he does not need, and more importantly, he wastes the time of important fellow-members of the organization or important visitors who know full well that they can only get an authoritative yes or no answer from the head man himself.

Why does this particularly annoying type of fifth wheel exist? The answer, simply enough, is, he bolsters the ego of the boss who uses him for the one purpose of filtering or weeding out the undesirables (from his viewpoint) who would otherwise consume his limited time. Generally speaking, these functions can be performed by an efficient secretary much more pleasantly and with much less pain. Furthermore, in the all important field of good public relations, a pleasant smiling woman can, and does, something for the big boss which he cannot all too often do for himself. She does a quick and efficient job of filtration, and equally important, she sends the chosen in with a glow of appreciated importance which helps the head man do his business far more efficiently than he probably ever realizes. However, as has been noted, this is a man's world in which we live. As the existence of that extra tail on the dog, or the fifth wheel on the motor car, the executive assistant proves only too well.

4. THE NEPOTIST

Ranking high in the hierarchy of the fifth wheel is the nepotist—this diffuser of illusions, chief of which is the belief that security can only be obtained through ties of blood. Despite much wailing and gnashing of teeth, the practicer of nepotism goes blindly on his way, filling the hearts of the worthy with black despair and pampering the chosen few who are the fruit of the family tree. The tales of envy, hatred, malice, and frustration, are legion amongst those whose lot is cast in an organization where nepotism in any form prevails. It is true that the vast majority of persons desire, above all things, "recognition", not always in the form of money, and frustration quickly warps their judgment, colors their thoughts and actions, and embitters their lives when they see the rewards in life passed out to those whose merits do not include that of productive efficiency.

Truly amongst the classical fifth wheels, which this 20th Century continues to provide endless power to generate, are the members of the boss's family, who quite frequently, even though possessed of ability in their own right, are denied the power to exercise it, simply because their colleagues at the collective work-bench cannot disabuse their minds of the fear that, come what may, blood will prove to be thicker than water. While the unwanted nephew may be a burden on the boss, he is an infinitely greater burden on the organization which sees in him the major obstacle to their own promotion. Blood is definitely thicker than water—but it can and does result in far too many fifth wheels.

The only case known to science, where a fifth wheel has any merit, is that in which a temporary floating wheel is attached to a test automobile for the provision of accurate engineering data based on the distance travelled, and related speeds.

In all other known and recorded cases, the fifth wheel has been demonstrated as an offense against the principles of sound mechanics and economics.

RECURRING MACHINE TOOL PROCUREMENT-CRISES IN U. S. OPERATIONAL MANAGEMENT

CAPTAIN R. E. W. HARRISON, USNR

The proven success of "management by the rule of exception," provides complete refutation of the theory and practice of "management by crisis".

Due to inevitable shortcomings in the system of democratically operated Government, coupled with average human performance efficiencies and normally expectable shortcomings, it is certain that crises will occasionally rear their ugly heads, thereby setting the stage for star performance by a modern Sir Galahad with his mighty sword.

The State of the Union would be Utopian, if we could so order our strategic and operational management that crises would never appear, but due to factors mentioned above, this is necessarily just a Utopian dream, and the best which can be done is to so manage affairs that the number of crises is reduced to a minimum, and unpleasant and dangerous events, which are reasonably avoidable, never appear over the horizon.

The purpose of this article is to invite attention to a type of fundamental crises which periodically demands all, and prompt, attention, i.e., the crises generated by a shortage of essential machine tools.

In each of the two major recent wars, and again in the case of the Korean affair, the U. S. has been confronted by a totally unwarranted crisis, brought on by a shortage of machine tools, in the production of which commodity, this country excels all others, this item being of the very essence of the pattern of success on which American wealth and power has been built, i.e., the lowly machine tool.

That the U. S., paramount as the world's designer and builder of the most productive tools which mankind has at any time been blessed with, when confronted with a deadly enemy, should have to go into an operational crisis because of shortage of the tools of production, is an indictment of the prevailing system, both Federal and commercial, of short term (12 months planning). This, coupled with failure to insure continuity of policy, by top permanent officials, and acute shortsightedness of people who still place faith in that outdated William Jennings Bryan philosophy—"when this country is threatened, 1,000,000 men will spring to arms"—constitute the three principal causes of our recurring dilemma.

WHY NEED THE CRISES OCCUR?

Progressive technology is a heady wine, but all arguments to the contrary, American business likes its heady wines and loves to live dangerously.

If any proof of this be needed, it is amply provided by the chart which depicts, who and what are the top one-hundred largest businesses in the U. S., plotted at ten-year intervals over the last fifty years. This challenging picture, the astonishing characteristic of which is the failure of the failures to come back, well proves the premise that love of mercantile adventure is inherent and specially potent when coupled with the Dun and Bradstreet statistic that the average life of an American business is just three years.

To get to the root of the problem of elimination of the perennial crisis of the lacking machine tools, due note must be taken of the shortcomings of the yearly Federal budgetary system, this 12-month period being the tool of the accountants which permits the quill drivers to keep their financial perspective in seeming order, simply by not straining their mental capacities as would be the case if they were asked to review the situation on a 2-year, 3-year or even a 5-year interval basis.

As a side issue, but an important one, it could well be, that the prevalence of chronic heart disease and associated ills amongst American businessmen is traceable to this yearly hassle with the comptroller and his aides, the accountants. These people are necessarily in our hair bedeviling us with their demands that we keep within last year's budget, that we concurrently devise next year's budget, while a review of the world and its problems is being made through a knot-hole in the fence, rather than from the vantage point of a lighthouse on the Rockies.

What this author is endeavoring to point out, is that the fundamental cause of the majority of crises which operational government management is called on to deal with, is self-generated and avoidable. If current example is needed, the present matter in regard to the raising of the limit of national debt, by an additional 15 billion dollars, is just that.

If further proof of traditionally short-range thinking of top budgeteers be needed, consider "horse and buggy" federal budgeting, figured out on the country store basis of cash in, and cash out, on a yearly basis. Even the most primitive of businesses uses two sets of books, one for the capital, and another for the operating account. Until this is done on a federal scale, national finances will never be in true perspective.

In the last analysis, a country, no matter how great its size and complexity, is nothing more than a big business, and if proof be required, consider the current statement of the Secretary of the Treasury to the effect that should Congress fail to raise the debt limit, and he, in turn, contracts more debt, it could happen that he would not be able to issue the salary checks to those on the Federal payroll. All of which brings out that operation of the U. S. is a business proposition, much in need of longer range thinking and sharper focus.

REMEDY

What is needed is a longer budgetary period, coupled with a five-year planning cycle, and these, in combination, will give us time to catch our cooperate breath and collaterally generate the quality of thinking and planning demanded by the hard times in which we live.

The sudden and unpredicated need for large quantities of tools means heavy financing. The 12 months life of a current budget seems short—but a 12 months delay in the procurement of needed tools could be fatal.

* * *

In well ordered commercial business, crises stink in the nostrils of the mighty, regarded as they are, as irrefutable evidence of poor management. The big boss, when confronted with too many crises generated in one of his departments, promptly and effectively gets rid of the cause by dispensing with the incompetent departmental manager concerned.

If the crises persist, in recurrence, are fairly widespread and serious, stockholders of the corporation, operating through their Board of Directors, relieve the man on the bridge and endeavor to secure for themselves a pilot more skilled in navigating their ship through the rock-strewn waters of modern business. Unfortunately, when we experience a machine tool crisis, we are at war, or near war, and that is a bad time at which to change leaders.

THE MACHINE TOOL FUTURE

In the dynamic economy of the U.S.A., the machine tool situation can never be static, and the foregoing statement automatically means that several basic situations governing machine tool demand are forever in a state of flux. To cite a few examples. The growth of the airplane industry, particularly the power plant end of that industry, has experienced rapidly improving technology and design, from the day that Lindbergh landed the "Spirit of St. Louis" in Paris. As of that date, Wall Street, exercising its legitimate prerogative and functions, started in to take a real interest in the future of aviation, and forthwith made available the money wherewith to pursue the improved technology, and to buy vast quantities of tools tailored to the new demand.

What happened? First impact was felt in the airplane drafting offices, in the pressing need for more rationally producible designs. Secondary impact fell on the machine tool industry, which had to meet new standards of performance with tools which would machine to superlative accuracy and finish, at a rate of efficient production outstripping all former records.

In the locomotive field, after several vigorous dying kicks, the steam locomotive has conceded defeat at the hands of the diesel electric brainchild of La Grange. Again, after hitting the man on the drafting board hard, the impact fell with hammer-like force on the machine tool industry to provide an accommodating range of machine tools which would manufacture these diesel electric work horses to standards of accuracy and finish, and at rates of production hitherto dreamt about, but never attained.

Currently, the gas turbine has the machine tool industry in a tizzy, inasmuch as turbine blades which will withstand greatest heat are automatically those which are least machinable; a fantastic struggle between advanced metallurgies and manufacturing techniques has been the result with new type machine tools in greater demand than ever before.

Nuclear power, now rearing its juvenile head, has emerged from the cocoon of the drawing board, and squarely hit the metallurgists and the tool engineers with problems of metal chemistry and fabrication quite new and different from previous problems, spectacular though these problems have always been.

Net result? Add to death and taxes—"change"—"perennial change".

THE ORDER OF CHANGE

Individuals of short memory, hence of limited perspective, loudly proclaim that there is no order of change, that it is sporadic, inspirational, unpredictable and uncontrollable.

It is the considered opinion of this author that these people are misinformed and a mathematical study of the order and rate of change in American technology could pay handsome dividends.

Individual companies have made such studies, and their ensuing spectacular success in anticipating in a profitable way the forthcoming demands of their markets, amply testifies to their wisdom of investment in this kind of exploratory thinking. The national picture, to be accurately depicted, calls for much more intensive study.

A relatively superficial study will show that major steps of advancement in American technology have occurred at approximately ten-year intervals, the point of turnover being astonishingly close to the beginning or end of each decade. It is not proposed in this article to explore or expound on the evidences which can be produced to back up this statement. The fact remains that those who have been granted a span of life which gives the individual a fifty-year perspective can and will identify the technological and accompanying economic change-overs which have occurred decade by decade as we have progressed up to this year of 1953.

What then is the significance to the overall machine tool situation of this ten-year cycle? Obviously, the ten-year cycle is the challenge, to produce the men with ten-year-ahead perspective.

If this precept be accepted, then the five-year cycle of major planning and budgeting review becomes even more logical considering the enhanced opportunities for economical advancement which such a procedure would provide.

FORECASTING AND BUDGETING THE MACHINE TOOL FUTURE

The problem of forecasting and budgeting the machine tool future, against a background of a broadly planned economy, as described in the foregoing paragraphs, becomes an orderly and feasible proposition, with collateral benefit of elimination of nationally endangering crises.

That the job needs to be done, there can be no shadow of doubt. The current proposal that we stockpile progressively a group of, for lack of a better name, that which is called the "elephant" type machine tool, is a sound proposal, but only a flea bite out of the total problem.

However, the current concept of design for an elephant type machine tool, is predicated on the prevailing forecast of airframe and wing design—elements which could radically change at short notice. Nevertheless, just as individuals pay our annual insurance bill praying that they will never have need to collect from the insurance company, so the U.S. must, using best available foresight, pay the premium imposed by the provision of hardware in the form of machine tools, just in case that emergency, an international crisis, should hit us again, as surely it will.

Deep probing research into end product design is the safeguard which will afford protection against making poor investments in "elephant" type tools, hence funds in support of sound, bold, research programs can be regarded as essential insurance against hazards inherent in the international future.

MACHINE TOOL CRISES

HISTORICAL SIGNIFICANCES

In the last two major conflicts America has been privileged to buy time in which to get ready to fight. In each case, sturdy allies have held the bridge, while relatively slow to move and slow to rearm America, flexed mighty muscles in preparation for a fight to the death.

The most optimistic forecasts fail to provide reassuring evidence that the privilege of buying time at the beginning of an international crisis will be accorded to the U.S. again. Indeed, it is more than likely that the U.S., which has in both major conflicts, thrown in the deciding element of power for a relatively quick decision, will be the major target at the very beginning of hostilities.

Sober forecasts of damage sustained in initial attack, indicate a third of our productive capacity could be knocked out in the first few days. Could more potent argument be developed in favor of generation of long range thinking and planning for the tools which we know we must have?

There are many with whom this problem has been debated, who, in good faith, maintain that the U.S. has matured in its economic thinking to the point where a machine tool crisis is avoidable. The facts of two years ago are still disturbing.

At the beginning of the Korean conflict in mid-1950, the call to arms generated a heavy demand for tools which the small and depressed machine tool industry was utterly unable to fulfill. The responsible authority, early in the crisis, proclaimed that machine tools were but as pots and pans, and would, under his then current scheme of planning, take their place in the priorities line-up for men, money and materials. This, despite the fact that the design of practically all weapons had changed completely since the end of World War II.

Korea, if you like to put it that way, was but a "police action." In a true national emergency such a philosophy and lack of action could have been fatal.

For nearly twelve vital, painful months the machine tool industry of the U.S. awaited a workable policy which would permit it to go to work on the national problem of new design arms production.

Good planning? . . . there just ain't none—yet.

Lack of planning for the machine tool future in the commercial field could well be "Achilles' heel" in the next conflict. The vision wherewith to generate and operate such a program does not grow on every tree—so—let's get busy.

MACHINE TOOLS FOR FUTURE DEFENSE PROGRAMS

In all the current discussions pertaining to disposal of the machine tools which have been accumulated as a result of World War II and Korean Action, little consideration seems to have been given to the underlying condition which generates the major problem at the beginning of each new war.

The condition referred to is that brought about by the rapidly changing design of the weapons of war.

As weapons and projectiles change, as they always will do, the machine tools required to make them change.

The advent of the Korean War rapidly demonstrated the inadequacy of the tools of World War II to produce the hardware required to fight the Korean War. This did not mean that all the machine tools used in World War II were inapplicable to the problems of the Korean War. Such a statement would

be far from the truth, inasmuch as the munitions demands generated by the Korean Conflict gobbled up in short order the painfully accumulated stocks of "reserve tools" which had been put into storage as a result of joint Army-Navy-Air Force action against the inevitable rainy day.

Just as the prices at which industry sells its products are in the main dictated by the degree of competition in the production field of that particular product, so the weapons wherewith we fight a war are dictated by the new types of weapons and new defense measures created by the new enemy.

This condition emphasizes the fact that the situation is forever mobile—never static. In other words, our potential enemies, in their armament fields, work unceasingly during the days of alleged and uneasy peace, their greatest ambition being to surprise us with the effectiveness of their new weapons on the day when they bring them into play.

A by-product of this condition is the reluctance of modern, large countries to disclose all of their hands in the opening phases of combat. The strategy employed is to keep the Sunday punch up the sleeve until the right moment arrives at which to deliver it.

All of the foregoing must be boiled down into the terms of a far-seeing and dynamic machine tool policy for the U. S. A.

The key element in this situation is the production pilot line. As new weapons and projectiles evolve from the drawing board to the pilot model, and then on to the pilot line, so automatically there are revealed basic requirements in the way of design for the machine tools required to make the new weapon.

Formerly a feeble attempt in this direction was made by the placing of meager "educational" orders for the munitions of war. These educational orders accomplished the important mission of keeping manufacturers "au fait" with techniques of manufacture, but they did nothing to fill the void of utter ignorance relating to new and different machine tools which would be required for manufacture of new weapons not yet in mass production.

There is no escaping the pilot line requirement. The Armed Services, once convinced that a new weapon is necessary wherewith to impose their will on the enemy, must seek from Congress the funds necessary wherewith not only to make the pilot models, but to also carry the exploration a stage further through the establishment of a pilot production line which will disclose the design of the production type machine tools required to mass produce the new weapons.

In a measure the arsenals performed this function in the past, but shortage of funds combined with lack of a well thought-out, complete program of attack on the problem, invariably resulted in the work stopping short at the crucial point of determining what, if any, new and different machine tools would be required to arm the country on mobilization.

It is strongly urged that a policy of pilot line production, designed to carry out explorations along the foregoing lines, be established as a matter of permanent procedure. The machine tool builders in return for contracts of minimum acceptable size will willingly cooperate with the Armed Forces in the production of the new machine tools required.

A collateral benefit to be derived will be the guidance provided, for the wise investment of the funds required to finance the conservative stockpiling of the new, different and advanced type machine tools, which are of the very essence of this country's ability to put its Armed Forces in the field with equipment equal to or ahead of that of any potential enemy.

COMBINATION PROPULSION PLANTS FOR NAVAL VESSELS

ACKNOWLEDGMENT

COMMANDER J. J. McMULLEN, USN, of the Bureau of Ships, Department of the Navy, is the author of this paper. It was presented at the semi-annual meeting of the American Society of Mechanical Engineers in Los Angeles, California, on 28 June, 1953.

The full speed required of any vessel fixes its total installed shaft horsepower. However, total shaft horsepower of combatant Naval vessels is utilized only a very small percentage of the total underway time. Thus weight penalties are incurred during the entire life of the ship to meet full power requirements that exist only occasionally. This problem has always been recognized. Even the ancient slave galleys, confronted with the same problem, found it was necessary to have a large number of normally superfluous oarsmen available when they entered battle.

Many schemes have been devised to maintain high efficiency at cruising powers and at the same time to meet the full speed power requirements of Naval combatant vessels. None has resulted in a drastic reduction in the total weight of machinery plus fuel; in fact some have resulted in an increase in total weight. The prospects of accomplishing major weight reductions in the foreseeable future with conventional steam or diesel propulsion plants is not promising for large powers. It is therefore vital that serious consideration be given to other arrangements, such as the application of simple, lightweight booster type gas turbines in combination with base load machinery, which has good thermal efficiency under cruising conditions. Substituting booster gas turbine power for the upper portion of the presently installed shaft horsepower would result in a plant of reduced cost, less maintenance, lower weight and less space.

A booster gas turbine is defined as a simple open cycle gas turbine with separate power turbine, but without refinements, such as intercooling and regeneration. Application of such units to propulsion of Naval vessels offers a sound and practical method of decreasing the machinery weights of some types of combatant vessels by as much as 20%. At the same time fuel consumption at cruising power is appreciably reduced thereby increasing the endurance by as much as 25%. Part of this increase in endurance is due to the better efficiency of the cruising plant which would operate at a higher per-

centage of its maximum power. In addition, the engine room length can be decreased and an approximatel reduction of about 25% of the molded volume will result. This is important because space is also a major military characteristic. The risk involved in construction of an experimental vessel is negligible, as will be demonstrated. Consideration already has been given to this type of plant, and much more will be given in the future. The gas turbine suited to such an arrangement will have low specific weight (about 2 lbs/SHP), a rating of 5000 to 10,000 shp, a specific fuel consumption of about 0.7 lbs/SHP-hr., the lowest feasible air mass flow and a full power life of approximately 500 hours.

The fundamental prerequisite for advantageous application of a combination plant is that the ship operate at high powers for only a small portion of its total life. This tactical requirement actually does exist for all combatant ships except submarines. It is particularly significant in light displacement, high speed vessels with limited bunker capacity, such as destroyers.

The curves of Fig. 1 shows the cumulative time versus power for a typical destroyer. They indicate that operation at more than half power occurs less than 1% of the total underway time. On the basis of 40,000 hours total underway time, this amounts to only 400 hours. In a ship requiring greater than 50% full power for more than a few percent of the total underway time, it would be necessary to use gas turbine booster units having longer life. In such instances the consequent increase in weight and space of the gas turbines, as well as the increased fuel consumption of the plant would somewhat reduce the advantage of a combination plant. Thus, the most advantageous application of combination plants to Naval vessels is clearly in ships which have a short time full-

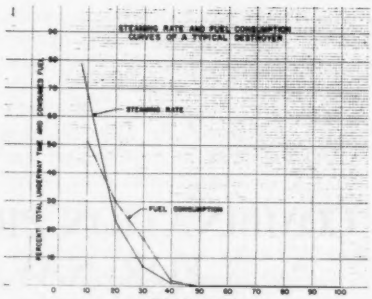

Figure 1 - Steam Rate and Fuel Consumption Curves for a Typical Destroyer

power requirement. As a matter of fact, the booster gas turbines would be paying for themselves even when not operating. Their mere presence and availability is the important point.

It is interesting to note that all Naval vessels may readily be placed in separate categories, according to their power requirements. Steaming rates for Naval vessels show that *all combatant vessels* (except submarines) use more than 50% full power for less than 1% of their underway time. The so-called auxiliary vessels use a larger percentage of their full power for a larger percentage of the total underway time. A third group of special ships have more or less constant power requirement at all times. Thus, based on statistical records of service conditions, combination plants using booster gas turbines are most attractive for the combatant group. Fig. 1a shows an average steaming rate curve for vessels of the auxiliary class. A significant feature of certain auxiliary vessels is that various types consume up to 85-90% of their total fuel in port. Thus, it would be advantageous to design their machinery plants for port operation rather than for underway operation. However, this is another subject.

A further and very enlightening classification of Naval vessel character-

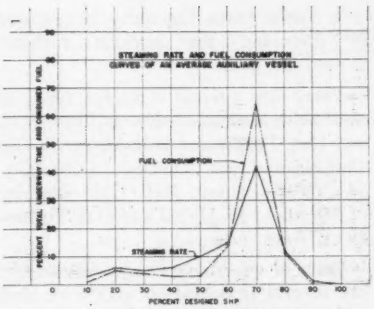

Figure 1a - Steam Rate and Fuel Consumption Curves for a Typical Auxiliary Vessel

istics according to relative machinery weights may also be made. For example, a destroyer has a machinery/total displacement weight ratio of about 25%, whereas the fuel/displacement weight ratio is only about 15%. Therefore, assuming reasonable fuel consumption, the most fertile field for gain in performance is in reducing machinery weight. On the other hand, a typical aircraft carrier has a total machinery/displacement weight ratio of only about 10%, whereas the fuel/displacement weight ratio is about 20%. Thus, in this type of ship it would be more advantageous to install a plant of higher thermal efficiency to reduce the fuel required for the same cruising range.

A major consideration in the design of a combination plant is the division of power between steam and gas turbine booster power. The optimum division of power must be made on the basis of operational requirements and will depend on the type of vessel, maximum desired cruising speed, the relative machinery weight, and the astern power requirement. At first it would appear that use of the lowest possible cruising power would give the maximum gain in weight of machinery plus fuel, but this is not quite true for at least three reasons. First, the weight of auxiliary machinery is not proportional to the cruising power. Secondly, the astern power requirement usually fixes the minimum capacity of the steam base load or cruising plant because boiler capacity must be provided. Thirdly, the operating time of the gas turbines should be kept to a minimum.

In determining the division of power, the maximum speed required with the cruising plant is important from an operational point of view because it is desirable, when cruising in formation, not to have to change from one plant to the other. Calculations indicate that a steam to gas turbine ratio of about 50% is probably desirable for most light displacement high speed combatant vessels. This higher percentage of steam power reduces the maintenance of the gas turbine portion of the plant and adds appreciably to its life.

The advantages of combination machinery plants are as follows:

1. A decrease in over-all weight and space, resulting in more speed for the same displacement, increased endurance or greater installed power.

2. A decrease in maintenance and repair; also easier handling during maintenance of the smaller, lighter machinery.

3. Quick starting: the ship can get underway on the gas turbines alone. This is a limited advantage because the ship cannot be backed down unless controllable pitch propellers or reverse gears are installed.

4. Fast acceleration from maximum cruising power to full power. The gas turbines require a very short warm-up period and will provide quick power.

It is important to note that in attaining the above advantages, the steam plant (in the case of COSAG) is *entirely conventional,* and is capable of driving the ship at about 80% of full speed. Moreover, the over-all plant reliability is greatly enhanced because of the presence of two separate and independent sources of power, tied together only at the reduction gear.

The main disadvantages of combined plants are:

1. The necessity for selecting a fuel acceptable to the gas turbine booster units. When the base load plant does not burn the same fuel as the gas turbines, the percentage of gas turbine fuel to base load plant fuel must be decided by operational requirements.

2. The arrangement requires a rather special gear configuration to accommodate the larger number of pinions.

3. Some extra ingenuity is required in disposing the various turbines around the gear.

There are several different types of combination plants, such as: 1) Steam and Gas Turbines (COSAG); 2) Gas Turbine and Gas Turbine (COGAG); 3) Free Piston and Gas Turbine (COFAG); 4) Diesel and Gas Turbine (CODAG).

Each of the above fundamental types has several possibilities, which we shall undertake to outline briefly.

STEAM AND GAS TURBINE PLANT

a. *Oil-fired cruising steam plant with gas turbine booster units for higher powers.* This combination looks most attractive for immediate application to light displacement ships of high power. The steam plant is capable of providing approximately 50% power, corresponding to about 80% full speed. Since the steam equipment is conventional, this combination provides the greatest gain with minimum engineering risk.

Determination of gas turbine booster unit rating is a problem of considerable magnitude. Smaller units are easier to install and replace; give a little better fuel economy (because they can be "cut out" when not needed, hence operate at near rated load most of the time); permit greater flexibility and reliability; have wider application to different ships; give an installation of longer over-all life. Disadvantages of smaller units over larger ones lie chiefly in the more complex gearing, and additional control equipment.

In general, it appears that the rating of gas turbine booster units for widest application in the U. S. Navy should be between 5000 and 10,000 shp. The lower limit is fixed at the rating where the diesel engine begins to become large and cumbersome, and the upper limit is fixed at a value that permits use of a reasonable number of units in most applications. Fig. 2 is a sketch of one possible arrangement for a combined steam and gas turbine plant using two 10,000 hp booster gas turbines and a 20,000 hp cross-compound steam plant. This figure shows only the port shaft of a possible engine room layout for a destroyer. The arrangement would permit all the booster gas turbines to be installed in a separate engine room and drive forward and aft through the main reduction gears of their respective shafts. Grouping the gas turbines in one space simplifies the ducting problem, permits the gas turbine fuel to be in adjacent tanks, confines the noise to one space and results in a satisfactory damage control system.

b. *Nuclear-fired cruising steam plant and gas turbine booster units.* Such a plant obviously depends upon a successful nuclear reactor, but it may have some outstanding advantages. Use of booster gas turbines will not reduce the size of the reactor, but will greatly reduce the size of the heat exchanger and associated steam machinery.

c. *Waste heat steam boiler operating on gas turbine exhaust.* This combination is shown in Fig. 3. In this arrangement a base load gas turbine (complex open cycle with intercooling and regeneration) is utilized in combination

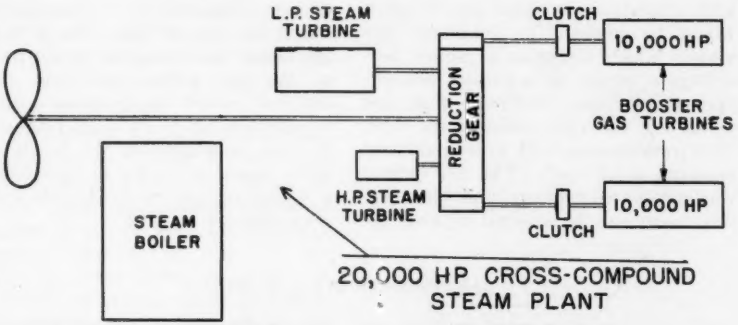

Figure 2 - Combination Steam and Gas Turbine Propulsion Plant (COSAG) - This sketch shows one possible arrangement for the port shaft of a typical destroyer. The booster gas turbines may be located in the same compartment with the steam plant or in a separate compartment. In the latter case, the bulkhead would be located between the reduction gear and the clutches.

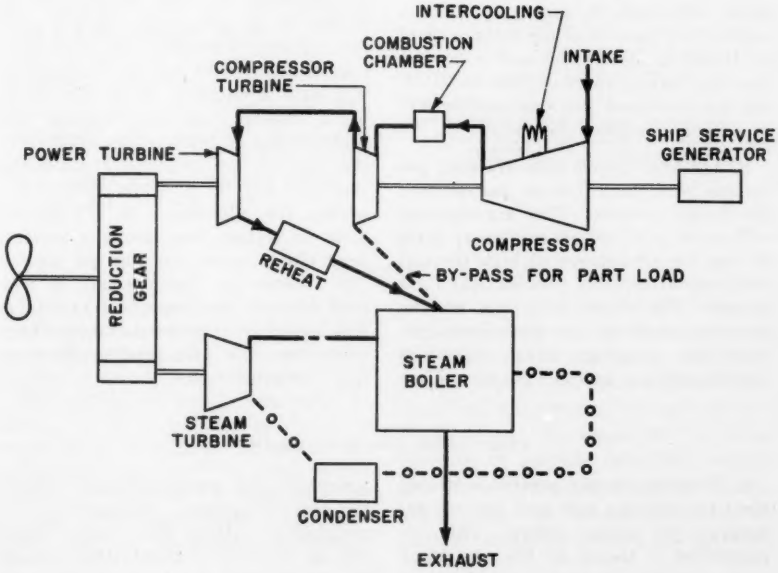

Figure 3 - Base Load Gas Turbine in Combination with a Waste Heat Boiler

with a steam cycle. This type of plant would be confined to auxiliary type vessels which steam at a higher percentage of power for a greater percentage of their total underway time and which are underway most of the time. This combination will give good fuel economy at all loads. The gas turbine combustion temperature and plant arrangement can be selected to give the desired distribution of load between steam and gas turbine. For part load and astern operation, the output turbine of the gas turbine and the reheat chamber would be by-passed; that is operation would be on steam plant alone. In this arrangement, the waste heat boiler would be simple in construction; it would require no brickwork and be very compact.

GAS TURBINE AND GAS TURBINE

a. *Complex open cycle cruising gas turbine plant (with intercooling and regeneration) with gas turbine booster units for higher powers.* Space and weight requirements of this all-gas turbine plant would be a minimum, and even on the basis of machinery weight plus fuel such a plant should have promise, based on results known to date. Many of the advantages of the combined steam and gas turbine plant mentioned above also apply to this type. Once a satisfactory base load gas turbine plant of 10,000 to 20,000 shp and a booster type gas turbine plant of 5000 to 10,000 shp are developed, this combination will be a very promising one.

b. *Oil-fired closed cycle cruising gas turbine plant with booster gas turbines for higher powers.* This arrangement will result in a compact machinery plant having the advantages of high thermal efficiency at cruising powers and light weight. The closed cycle gas turbine plant has excellent part load characteristics for cruising. When combined with booster gas turbines for the higher powers the size of its air heater, regenerator, and other components is greatly reduced, making it an attractive alternative for combatant vessels where low fuel consumption is of an essence; for example, an aircraft carrier.

c. *Nuclear-fired closed cycle gas turbine plant with booster gas turbines for higher powers.* This type of plant is similar to the nuclear-fired steam plant in paragraph 1b. The main difference is that the closed cycle gas turbine plant may provide a smaller and more compact cruising plant than the steam cycle. The first application of nuclear power to a closed cycle gas turbine will probably use an intermediate coolant for the reactor, but eventually gas-cooled reactors will be possible. When this occurs, the advantages of a combined plant in certain ships using a nuclear-fired closed cycle cruising gas turbine plus booster gas turbines will be lessened because the large heat exchanger will have been eliminated and the closed cycle alone will give good performance over the entire range.

FREE PISTON AND GAS TURBINE

a. *Free piston gas generator-turbine plant for cruising and with booster gas turbines for higher power.* This arrangement is shown in Fig. 4. Many interesting variations are possible and need to be evaluated. For example since the exhaust of the free piston gas generator still contains about 75% of the original oxygen, afterburning is a possibility. About 30% extra power can be obtained at about 10% increase in specific fuel consumption, thus decreasing the required booster power at some expense in cruising economy. This

combination provides a cruising plant of thermal efficiency equal to or better than that of a diesel, and with the flexible power take-off possibilities of a turbine installation.

b. *Free piston gas generator-turbine with afterburning firing a waste heat boiler for auxiliary purposes.* This combination offers an excellent means of providing steam for hotel and auxiliary purposes. Afterburning can be accomplished either before or after the gas turbine, or in both places, depending on the relative demands for power and steam. The arrangement is also shown in Fig. 4.

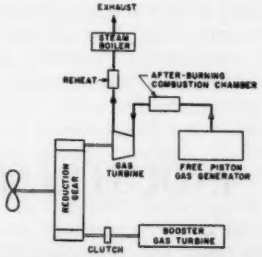

Figure 4 - Combination Free Piston and Gas Turbine Propulsion Plant (CGFAG) - The after burning combustion chamber would be used only as booster power in much the same fashion as the booster gas turbines. Reversing could be accomplished either with a controllable pitch propeller or an astern gas turbine. The steam boiler is only for auxiliary and hotel purposes.

DIESEL AND GAS TURBINE

a. *Diesel engine for cruising with booster gas turbines for higher powers.* This combination appears to be most adaptable to small high-speed craft such as PT boats. The diesel engine and the gas turbines can be hydraulically coupled to the same reduction gear as shown in Fig. 5. Reversal can be accomplished with either a controllable pitch propeller or a reverse gear. The controllable pitch propeller would also eliminate the two-speed clutch on the diesel engine which furnishes power at both cruising and full speed.

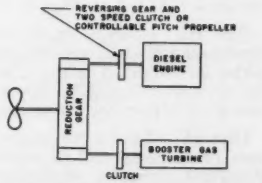

Figure 5. Combination Diesel and Gas Turbine Propulsion Plant (CGDAG) - This combination would use either a controllable pitch propeller or a two speed clutch and reverse gear on the diesel engine. Either arrangement would permit the diesel engine power to be utilized at all loads.

SUMMARY

It is painfully obvious that the first installation of a combination plant must await the development of a successful marine booster gas turbine unit. Such a unit will be of tremendous value to the U. S. Navy because of the wide range of its usefulness. It can be installed advantageously in small, high-speed craft such as PT boats in combination with lightweight diesel engines, and in high-speed combatant vessels with limited bunker capacity, such as destroyers. Intelligent application of this important prime mover will greatly improve the operating characteristics and effectiveness of many of our Naval vessels. Development of a versatile unit of suitable durability, weight and fuel consumption should bring ample reward to the enterprising manufacturer who first achieves the objective.

INDUSTRIAL NUCLEAR POWER

ACKNOWLEDGMENT

This article actually consists of four separate articles published under the general title "Industrial Nuclear Power" in the May 1953 issue of "Nucleonics", copyrighted by McGraw-Hill Publishing Company, 1953.

Part I, "The Key to Atomic Power", written by MR. KARL COHEN, Vice President of Walter Kidde Nuclear Laboratories, Inc., discusses the possibilities of achieving low-cost reactors and the availability and price of uranium.

Part II, "Foreign Market for 'Package' Nuclear Power", appraises the power needs of foreign countries. It was prepared by MR. HOWARD C. GARY, of the McGraw-Hill Department of Economics.

Part III, "Changes in the Atomic Energy Act", was written by MR. OSCAR M. RUEBHAUSEN, chairman of the New York City Bar Association's Special Committee on Atomic Energy. The article recommends four changes to the McMahon Act to foster industrial development of nuclear power, and is based on a paper presented before the American Power Conference in Chicago on 25 March, 1953.

Part IV, "Recent Advances in Reactor Technology", treats in detail the problems of breeding and of achieving high flux. It was written by MR. ALVIN M. WEINBERG, Director of Research, Oak Ridge National Laboratory, and is based on a talk given at the North Carolina meeting of the American Physical Society on 27 March, 1953.

I. THE KEY TO ATOMIC POWER

The proper role of private initiative in atomic development is now being seriously reconsidered for the first time since the Congressional hearings of 1945-1946, which preceded the passage of the McMahon Act. Public and congressional support for broader industrial participation in atomic development is principally sustained by the prospect of civilian atomic power, since economic atomic power is not unnaturally associated with commercial plant operation. For this reason, studies of the economics of atomic power have unusual present interest.

Most observers conclude that power cannot be produced economically without major advances on present technology, except as a by-product of plutonium manufacture. This indicates, to one school of thought, the necessity for a program on breeder reactors; to another, the need for a guaranteed price of plutonium; and to still others, government financing of the reactor. These diverse points of view lead to equally diverse opinions on the urgency and method of improving the McMahon Act; an extreme view is that a more favorable economic forecast should be a prerequisite to amending the law.

The present article takes a more optimistic view of the economic possibilities. We believe that dual-purpose reactors, although offering immediate economic feasibility, are not the only, or even the preferred method of approach. There is reason to believe that single-purpose plutonium reactors will produce cheaper plutonium and that single-purpose power reactors can produce economic power.

The substance of this article will be a careful analysis of the economic assumptions on which power cost estimates have been based. What is perhaps not fully appreciated is that the various experts base their cost estimates on different assumptions; and the conclusions depend strongly on the assumptions. This is not merely a question of disguising true and official figures for security reasons. A theme of the present paper is the slightly heretical one that official cost figures for government operations, even if known, would not always be the appropriate basis for cost estimates of commercial power.

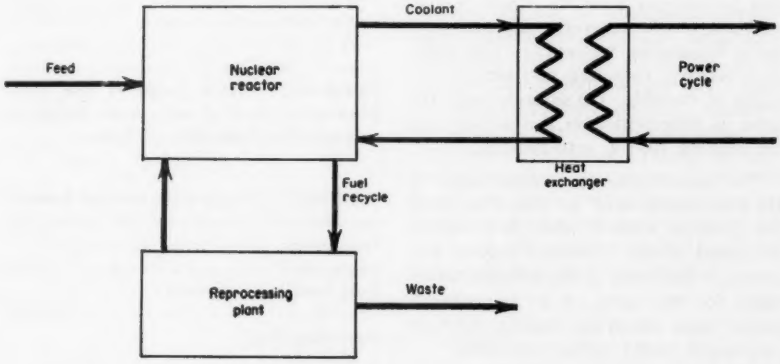

Figure 1.

COST ELEMENTS

Operation of a nuclear power plant is shown schematically by Figure 1. Feed, which may be fissionable or fertile material, or a mixture of the two, is fed into the reactor at a rate sufficient to maintain the reactivity. Spent fuel is recycled through a chemical and/or metallurgical reprocessing plant at a rate determined by one of a number of factors: radiation damage, loss of reactivity, etc.

Waste material is drawn off from the reprocessing step. The waste material is likewise a mixture of fertile and fissionable materials and may, in some instances, be more valuable than the feed; the use of the terminology "waste" and "feed" indicates merely the direction in which these products flow. For completeness an isotope separation step might be included in the reprocessing cycle, but this can be omitted without real loss of generality.

The reactor also produces heat, and this is transferred through a heat exchanger to the working fluid of a power cycle. It is approximately correct to say that the power cycle, from the heat exchanger on, would be the same as the power cycle of a coal-fired plant. There is some indication that the economic operating pressure for steam plants with low fuel costs is less than that of coal-fired plants, but for the purposes of concentrating attention on the reactor, it is expedient to ignore this difference.

The illustration applies equally to the steady-state operating condition of reactors which burn U^{235} and convert fertile material to fissionable material, and to breeder reactors which would consume fertile materials only and produce fissionable materials. The relation between recycling and purging to waste is variable; the once-through reactor is represented in this scheme by the limiting case of zero recycle.

The contribution to power costs of the plant components on this flow sheet are given in Table 1, which is discussed in detail under "Single-Purpose Reactors." In Table 2 the corresponding costs for the parts of a conventional power plant which the reactor and heat exchanger would replace are listed.

When we try to put numbers into Table 1, we run into difficulties, because there is no general agreement about the costs of the reactor or the reprocessing steps which would be appropriate for private operations. To surmount the present difficulty of a complete lack of commercial experience, the plutonium-plus-power reactor proposal has been advanced. In this way it is hoped to sidestep the economic problem.

TABLE 1—Costs of Nuclear Power*

Investment	Case A	Case B
Reactor and heat exchanger		
Reprocessing plant		
Fuel inventory		
Total	$225/kw	$210/kw
Operating Cost (mils/kwh)		
Reactor and heat exchanger operation	0.3	0.3
Reprocessing plant operation	0.3	0.3
Capital charges	4.5	4.2
Feed cost	—	0.3
Credit for waste	—	—
	5.1	5.1

*Excluding turbine and electrical generator. 80% service factor.

TABLE 2—Costs of Conventional Power*

Investment	
Boiler	
Fuel handling equipment	
Total	$80/kw
Operating Cost (mils/kwh)	
Boiler operation	0.6
Capital charges (at 14%)	1.6
Fuel cost (coal at $7.50/ton)	2.9
	5.1

*Excluding turbine and electrical generator. 80% service factor.

DUAL-PURPOSE REACTOR

The central issue here is what value to assign to plutonium. The proponents of a dual-purpose liquid-metal-cooled reactor write (1):

" . . . preliminary estimates of the cost of plutonium production in a dual-purpose reactor of this kind were made and compared with the cost in present-day reactors designed to produce plutonium only.

"Quite without regard to power production, it turns out that the liquid-

metal cooling represents, in itself, an advance in technology which promises a reduction in costs.

"Because of the high cost of plutonium, the reactor should be designed and operated so as to produce it as cheaply as possible regardless of the effect on the efficiency of the power production. It turns out, however, that one of the big advantages of liquid-metal cooling is that, after plutonium production has been optimized, it is still practical to generate power. It is in this sense that the two products are economically compatible.

"Unless some still cheaper method is found first, present-day government plants would serve as the basis for determining the competitive price of plutonium. In comparing government costs with private industry, the same bookkeeping methods would have to be used along with the same tax computations and depreciation periods."

This answer not only sets a price on plutonium, but also makes the costs of uranium and chemical reprocessing immaterial, since they are part of the costs of the yard-stick plants. From the standpoint of the government, the principal unsatisfactory feature of the solution would appear to be a requirement to guarantee the market for plutonium (2). Such an objection would, of course, disappear with an upward revision of the estimated plutonium requirements.

There are other difficulties which appear to be more fundamental. One is suggested in the phrase "unless some still cheaper method is found first." Here we have room for endless speculation on the relative (paper) merits of various reactors.

Another difficulty is revealed by the phrase "the big advantages of liquid-metal cooling is that, after plutonium production has been optimized, it is still practical to generate power." This means that with some coolants, optimum plutonium production is not compatible with power generation. Taking the two phrases together we have an indication that lowest price plutonium may not be associated with power generation at all —a proposition that certainly takes the bloom off dual-purpose reactors.

SINGLE-PURPOSE REACTORS

It would seem from the preceding discussion that the dual-purpose reactor concept may not automatically eliminate all present problems. Let us, therefore, consider single-purpose reactors for the production of power and see how far away we are from economic feasibility. (Refer again to Table 1.)

The obvious proposition for nuclear fuel is to strive to make the fuel cost negligible and then to use up the available credit as capital cost of the nuclear reactor. For example, if as in Case A all fuel charges were zero (that is, in Table 1, fuel cost less credit for waste equals zero) and if the costs of operating the reactor and chemical plant were no more than 0.6 mil/kwh, we could afford 4.5 mil/kwh of capital charges, which is equivalent to an investment of $225/kw.

The $225/kw has to be allocated to three items, and this is not easy to achieve. Values quoted in the literature vary from as low as $280/ kw (3), to $5-600/kw (4), to an astronomical $1400/kw (5) for the ship propulsion reactor. It would seem from these numbers that we must squeeze both fuel costs and reactor and reprocessing costs to the limit to achieve economic nuclear power. In this way, one appears to be led to consider the design of advanced breeder reactors of a novel type, whose realization is some years away.

However, other lines of attack are

possible. We start with the observation that if uranium is basically a cheap fuel, it is not entirely logical to do the utmost to economize it. Suppose that instead of trying for a zero fuel charge, we accepted one which would be one-tenth that of coal, i.e., 0.3 mil/kwh. In this case the allowable capital investment for the reactor plant would be \$210/kw, (Table 1, Case *B*) which to be sure is slightly reduced but may be easier to achieve. We might, for example, be able to lower the chemical reprocessing plant cost—or in exceptionally favorable cases even eliminate it entirely; we might be able to reduce the fuel inventory or use a cheaper fuel; and we might be able to build a cheaper reactor. The most interesting possibility is that some of these things could be accomplished without waiting for a brand new technology.

Let us see how much uranium we have to consume to achieve 0.3 mil/kwh. The fission of 1 gm of uranium gives about 6000 kwh of electricity; at 0.3 mil/kwh we can pay \$1.80/gm or \$800/lb. of fuel used. This rules out, to begin with, the use of pure fissionable materials, whose costs have been quoted (5) at \$20/gm. Let us suppose, following Zinn (6), that we use natural uranium as fuel in a regenerative reactor, that radiation damage will not cause trouble until 1% of the uranium is consumed, and that we must then withdraw and discard the irradiated fuel, thus eliminating all chemical reprocessing charges.

In this case 0.3 mil/kwh fuel cost would require uranium at \$8/lb. If the uranium cost were higher, we would have to irradiate longer, or accept a higher fuel charge. What is clear from this hypothetical example is that the fuel for this type of operation will have to be wholly, or largely, natural uranium; and that the price of uranium will have a marked effect on the economics of the whole enterprise. To evaluate the potentialities of this reactor concept, we shall be obliged to take a closer look at the availability and price trend of natural uranium.

THE PRICE OF URANIUM

Several recent authors (4, 6, 7) have been satisfied to use the figure of \$35/lb for uranium metal in a reactor, but Young has quoted (8) a figure of \$10/lb, and a recent *New York Herald-Tribune* dispatch (9) gives the Canadian price as \$7.25/lb. of U_3O_8, which would be more in agreement with the latter figure. The key to this apparent discrepancy is the observation that there is no free market and that we are talking of production costs and not prices. Uranium is currently produced from high-grade deposits (Belgian Congo, uranium content of the order of 10%), medium grade deposits (Canada, uranium contents up to 1%) low-grade deposits (Colorado, order of 0.1%), and as by-products of other mining operations (Florida phosphates, 0.01%). It is plain that the American producers have the highest costs. Does the effort to develop the high-cost areas necessarily mean that the military demand for uranium is greater than the potential production of all low-cost producers? This conclusion is not certain. The strategic advantage of having production facilities in the continental United States might warrant support of high-cost operations even if additional low-cost production could be developed overseas. Unless we postulate an indefinite expansion of military demand, new discoveries will result in availability, at least for a few decades, of low-cost uranium for industrial use.

The case of indefinite expansion of military demand would perhaps push the uranium price up; but this would be associated with a concomitant expansion of demand for plutonium. One could then expect a price for plutonium which would pay the freight. There is a logical inconsistency in simultaneously assuming a static plutonium demand *and* a high price for natural uranium for commercial use.

In the price which the government pays for uranium from low-grade ores, we have a fine example of the truism that a perfectly valid price for the government may not be the commercial cost of a product.

THE URANIUM SUPPLY

Let us begin with an analysis of the availability of uranium. There are two equally relevant facts to be considered in evaluating the energy potential of a fuel. One is the current rate of production; the second is the estimated recoverable reserve. The second figure has been estimated (10) at 25-million tons of uranium,* or an energy reserve in U^{235} alone of $12Q$ ($1Q = 10^{18}$ Btu). It is instructive to compare this number with the total world reserve of coal which the United States Bureau of Mines has estimated as 68 Q, not all of it economically recoverable.

More to the point is the magnitude of the present rate of production. No official estimate has been published. Pre-war production potentials were about 1000 tons of U_3O_8 per year (11). We can get a rough idea of the magnitude of the operations planned at Beaver Lodge, Canada, from figures published March 30, 1953 (9). It was disclosed that ore in the Gunnar lode which is a privately-owned zone 25 miles west of Eldorado's Ace mine, assays 4.5 lb U_3O_8 per ton, and that preliminary refining operations at Ace mill will be 500 tons or more a day at the start. Multiplying these figures together would give 400 tons of U_3O_8/year. With these numbers in mind, 1000 tons/year of uranium does not sound like an unattainable production figure. We should be well satisfied if atomic power were supplying 10% of the country's power needs in 10 years; this would require the annual consumption of about 10 tons of nuclear fuel. It is patent that this could be done, using only 1% of the potentially available energy.

It is interesting to reflect that the present estimated world oil reserves are 0.4 Q, and that the United States annual consumption of oil is 0.01 Q, the amount of energy in the fission of 140 tons of uranium. The oil companies, the airplane engine and airframe manufacturers, and the automotive industry, to mention just a few, have built up sizeable enterprises on this negligible amount of energy. Although it would appear necessary ultimately to supplement the oil supply by hydrocarbon synthesis, in spite of repeated warnings by United States Department of Interior experts over the last 35 years that we are in imminent danger of running out of oil, it has not yet proved economic to make oil from coal.

In a similar way, there is nothing in the present fuel resource picture to compel us to await the design of breeding reactors before utilizing atomic energy for power; this argument for delay makes even less sense when we realize that in the meantime in our production reactors U^{235} is being consumed and the heat is being wasted. The argument has been advanced that 12 Q is not enough to sustain a sta-

*Recoverable uranium is defined as that obtainable at $100/lb. or less for metal in billets.

tionary power industry in the year 2000, and that we should, therefore, proceed now to develop breeder reactors which would use the more abundant U^{238}. The problem which we have to deal with, however, is not how to sustain a stationary power industry on uranium, but how to start one, and on this topic long-range planning considerations are unconvincing.

CONCLUSION

We see from the preceding sections that there is evidence that uranium will be abundant and cheap enough to be used as a fuel, and that it will not be necessary for the next several decades to go to extreme lengths to conserve it. Our studies of the economics of single-purpose stationary power plants show that reactors that consume uranium to a limited degree would be economic if they were built for less than $200 per kw. The key to commercial atomic power is a low-cost reactor. It is our belief that this objective can be achieved by inventive design with only minor advances to present technology.

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II. Foreign Market for "Package" Nuclear Power

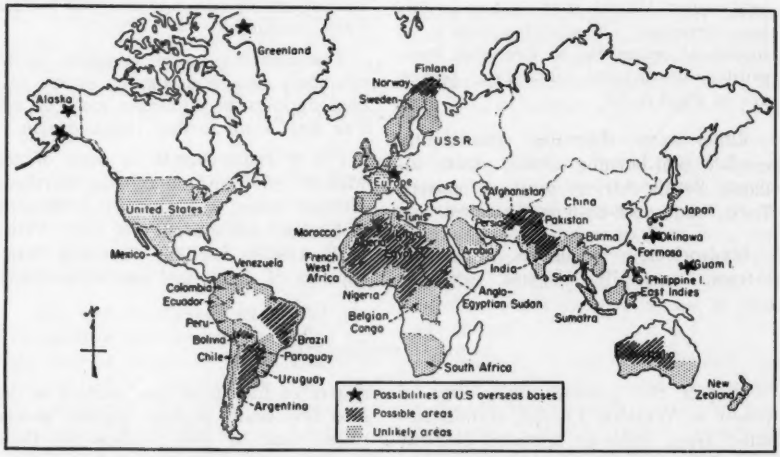

Fig. 2. Possibilities for economic use of high-cost package nuclear power

A survey of possible foreign markets for reactor power plants to supply 5000 to 50,000 kw of electric power in the cost range from 2½ to 4¢/kwh indicates that there are areas in the world where such power could be competitive with existing power supplies or could supply needed power that does not exist now.

In a previous article,* a survey of U. S. domestic and overseas military markets for this type of power was described. For both these surveys, the same general principles apply; in the case of foreign markets, the general principles are particularly important since actual generating costs outside the U. S. are not available. An area that will find package nuclear power feasible must meet these four criteria:

1. It must be capable of using a firm flow of power. If not, the relatively high capital costs of the reactor would decisively give the advantage to lower-cost conventional facilities.

2. It must be fairly remote from cheap supplies of coal. Coal is a high-bulk, low-value item and, therefore, transport costs tend to be high.

3. It must be without access to reasonably priced hydroelectric facilities.

4. It must be unable to use oil or natural gas for reasonably priced power generation. It was shown in the first survey that unless diesel fuel costs more than about 25¢/gal, package nuclear power cannot possibly compete with diesel.

*Richard W. Everett. Market for "package" nuclear power, Nucleonics No. 11, 4, 32 (1953).

UNLIKELY AREAS

With these criteria in mind, many areas can immediately be eliminated from consideration. Western Europe, for example, has adequate sources of power. The coal bottleneck in the early years after World War II has largely been removed. The area has been a big industrial center for so long that basic utility installations, including power, are in good order.

Other areas that can conveniently employ coal-burning steam plants include South Africa, most of eastern India, and south-eastern Australia.

Hydroelectric resources in central Africa, especially Nigeria and the Belgian Congo, appear adequate for all foreseeable power requirements. Certain parts of Chile and Brazil, as well as most of New Zealand, enjoy very satisfactory hydro potential. Uruguay also has reasonably adequate and well-located hydro resources.

The combination of adequate hydro resources and good supplies of low-cost coal appears to eliminate most of the Far East from further consideration.

Power requirements in most of the Middle East and along the northern African coast, as well as in Mexico, Colombia, Ecuador, Peru, and Venezuela, can be filled by relatively cheap supplies of diesel fuel and natural gas.

GENERAL POSSIBILITIES

Despite the general availability of power in Western Europe, certain isolated areas, such as northern Norway and Finland, may be able to use the relatively high-cost package nuclear power.

In the Middle East, only Afghanistan does not have oil. In addition, this small mountainous nation has no coal. Preliminary investigation suggests that the capital city of Kabul may well be a potential site.

Certain inland portions of India and Pakistan are handicapped by their inability to produce reasonably priced power. Since both nations in the subcontinent hope to achieve a substantial degree of industrial development in the next few years, package nuclear power plants may be able to help fill their power void.

Large areas in north-central Africa—including the Sudan, French West Africa, Libya, and Algeria—are remote from coal, oil, and hydro resources. If the programs of technical assistance sponsored by the United States and the United Nations reveal the existence of a moderate industrial potential in this area, nuclear reactors may play a key role in the power development.

The area of greatest promise, however, seems to be the South American continent.

SOUTH AMERICA

The countries in South America that merit further consideration are Brazil, Chile, Argentina, Bolivia, and Paraguay. The rest of the Latin Republics have no problem because of their accessibility to plentiful supplies of oil.

Brazil. This country has tremendous hydro potential. Good waterpower resources are located near the key industrial region of Sao Paulo. Other regions of this vast land that appear to have considerable industrial potential,

however, are not so well endowed. In these spots, and the area north of the Volta Redonda is an especially prominent one, package power offers an exciting possibility.

An additional factor that enhances the attractiveness of nuclear power is the relatively high cost of imported diesel fuel at Brazilian ports. The cost hovers about 25¢/gal, which is just about the point where disel power and package nuclear power might become competitive.

Chile. There is considerable hydro potential in this country also, except in the north, and the nitrate fields in that section of the country require a firm flow of power.

The cost of diesel fuel at the ports is a cent or two cheaper per gallon than the cost at Brazilian ports. But when the cost of transporting the fuel inland is considered, the price to users goes over the 25¢/gal mark. So, despite the abundance of hydro potential, there may well be an attractive market for package power in northern Chile

Argentina. The large hydro potential in this country is in the foothills of the Andes, in the west, whereas the centers of population and industrial development are chiefly in the east. Imported diesel fuel costs over 25¢/gal.

It would appear likely, therefore, that many areas in Argentina offer attractive possibilities for package reactors. Whether the political situation there allows for real cooperation with the U. S. is, of course, a question.

Bolivia. Although a mountainous country, Bolivia's hydro potential does not seem suitably located to provide continuous and economic power to the many mines. Power experts have suggested that many mining installations in this land-locked country may be capable of making effective use of package power.

Paraguay. Lacking both coal and oil, and with hydro resources not conveniently located with respect to markets, this country offers promising possibilities. The fact that the railroads have wood-burning locomotives indicates Paraguay's power needs.

THE FUTURE

Further study and investigation may well turn up other isolated markets for relatively high-cost power. There may even be some good sites in nations where there is an adequate over-all supply of power. Fairly remote mining installations seem to be the type of project that can benefit most from package nuclear power.

The argument is frequently advanced that the high capital costs of investing in nuclear power would be a difficult barrier for most power-hungry nations to hurdle, the more so since the outlay would have to be in scarce—for them—dollar exchange. On the brighter side is the fact that this seems to be precisely the sort of project that can be financed with the help of the Export-Import Bank or the International Bank for Reconstruction and Development.

The first article in this series concluded that the outlook was not too promising for strictly commercial use of package reactors in the U. S. An appraisal of foreign markets, however, leads one to believe that there are several nations which might find package power an attractive solution to the power-shortage problem.

III. Changes in the Atomic Energy Act

The Atomic Energy Act represents a unique departure from the traditional principles of our Government. The legislation was prepared by a nation deeply disturbed by, and deeply ignorant of, the force with which it must deal. Because of some misconceptions we adopted a legislative expedient which is inconsistent with the principles that have made us strong as a nation.

I think the time has come not only to take another look but to restore atomic energy to the normal framework of our democratic society.

Such a re-examination must precede any sound Congressional legislation in this field. Such a re-examination, moreover, is urgently needed if we are to drive forward with vigor and imagination to a maximum realization of the potentialities inherent in the atom.

Even now, however, it is possible to visualize the outlines of a new atomic policy. Four elements of such a new policy are reasonably clear. If a new atomic policy is to be founded, as I believe it should be, on these four new elements, an amendment of the Atomic Energy Act is clearly required.

OWNERSHIP OF FACILITIES

Section 4 of the Atomic Energy Act provides that the United States shall be the exclusive owner of all facilities for the production of fissionable material except, to a limited extent, certain research facilities.

If there were to be a transfer of all atomic facilities to some international body, Government ownership of atomic facilities might still be wise. It would certainly simplify the legal steps for such a transfer. Since there is to be no such transfer, however, technical ownership in the United States Government serves no useful purpose which could not be as readily achieved in some way more consistent with our traditions. On the other hand, the elimination of this provision of the Act will not of itself bring about private participation in the atomic energy business. But, unless private ownership of facilities is permitted, private participation may be needlessly slowed up. Private ownership, it is said, will facilitate the financing of private atomic enterprises and will contribute to management efficiency. Repudiation of the principle of exclusive government ownership of atomic facilities will also, I believe, have a healthy effect on the national approach to atomic problems. It will shift some of the responsibility and, with it, the initiative to private hands.

OWNERSHIP OF FUEL

Closely related to this question of the ownership of atomic facilities is the problem of who may own fissionable materials. In a sweeping provision, Section 5 of the Atomic Energy Act automatically vests in the Atomic Energy Commission all rights in any fissionable material which is within the jurisdiction of the United States.

Fissionable materials are clearly affected with the public interest. The public has a vital stake in their manufacture and in their use. This public interest can be served only by the very

closest of governmental regulation. Such regulation should extend not only to matters of public health, safety and the national security, but also to the allocation, utilization and requisitioning of critical items. These are clearly difficult problems. They will require wise administration and flexible regulation.

Complex as these problems are, absolute government ownership of fissionable materials is not the answer. With ownership of fissionable materials goes the main initiative for forward progress in peaceful atomic uses. With it also go the burden and the risks of failure. Such initiative and risk-taking are not the distinguishing characteristics of government—no matter how able and enlightened. Initiative and risk-taking are, however, the very essence of free private enterprise.

CONTROL OF INFORMATION

The section of the Atomic Energy Act which above all others, to my mind, urgently requires revision is Section 10. Section 10 defines what constitutes "restricted data." It gives the Commission control over the dissemination of such data and severely punishes any unauthorized or unlawful disposition of such data.

The key provision is the definition of restricted data; it is exceedingly broad.

We would expect restricted data to include all data concerning the manufacture or utilization of atomic weapons. The Act, however, goes much further. It also provides that restricted data shall include all data concerning "the production of fissionable material" and, what is more, "the use of fissionable material in the production of power." The only exception is for "data which the Commission determines may be published without adversely affecting the common defense and security."

Thus, all data in the atomic energy field is, you might say, born into this world secret; and it stays secret until the Commission feels that it can meet the burden of proving that the release of such data cannot adversely affect the common defense and security.

Such a definition is unduly restrictive. If interpreted literally, little could be released. For even the most innocuous information might, under certain circumstances, adversely affect the common defense and security.

Our basic atomic legislation, I think, should reflect a more balanced approach to secrecy. There should be more of a weighing of the total good that may result from publication as against the possible harm. There should be more emphasis on the affirmative policy of achievement as against the dubious gains from concealment. There should be some difference in treatment as between data pertaining to military applications of atomic energy and the nonmilitary processes. The legislation, moreover, should reflect that, in the last analysis, real security will come only if our rate of progress exceeds that of our enemies. Hence, control over atomic information should be directed above all else, not to the end of concealment, but to the assurance of our own maximum possible rate of progress in all phases.

Section 10 of the Atomic Energy Act should be revised. In this connection I make two specific suggestions.

First, I suggest that the definition of restricted data be limited only to data concerning the manufacture or utilization of atomic weapons and such other data as the Commssion, from time to time, may affirmatively declare cannot be published without adversely affecting the common defense and security. Under this proposal data concerning the pro-

duction of fissionable material or the use of fissionable material in the production of power would become public unless the Commission found positive reasons to the contrary. The burden of proof would be completely reversed.

A change in the definition of restricted data would not, of itself, be enough. Habits formed in the six years of operation under the present law may be hard to break. So my *second* suggestion would be, once the definition was changed, that the Commission appoint a special panel to review all secret data in the light of the new policy. Such a panel should have a specific mandate from the Commission to declassify all information which is not in the weapons field unless it is satisfied that such declassification would adversely affect the common defense and security. So much for Section 10.

PATENTS

The fourth principal area for legislative attention is Section 11, patents.

As the Act now stands no patent shall be granted for any invention or discovery which is useful solely in the utilization of fissionable material or atomic energy for a military weapon, and no patent shall confer any rights to the extent any invention or discovery is used in the utilization of fissionable material or atomic energy for a military weapon. With such provisions I personally cannot disagree.

The Act, however, goes further. It provides that no patent shall hereafter be granted for any invention or discovery which is useful solely in the production of fissionable material. Likewise, it denies patent rights with respect to any invention or discovery to the extent that it is used in the production of fissionable material. I do not see what is to be gained by such a repudiation of the incentives and benefits of the patent system in the case of fissionable material for other than military purposes.

If inventions or discoveries have uses which are not military or governmental, then the rights to such private uses should be enjoyed by those who have contributed to their discovery.

If the government makes a discovery through government-financed research, there should, clearly, be no private patent rights. If, on the other hand, the know-how or the capital of private industry is drawn upon in the making of such a discovery, then the contribution of private industry to that discovery should be recognized in the distribution of the patent rights.

The form of such recognition will, of course, vary in every case. What is fair will depend on a wide variety of factors. Such matters are, however, subject to negotiation and reasonable allocation. It is only with the principle of fair recognition for the contributions of private persons that I am presently concerned. To the extent that the Atomic Energy Act repudiates this fair principle in the nonmilitary and nongovernmental uses of atomic energy, I believe it should be amended.

Only with a change of policy can we bring into play the full vitality of the American people and American industry. We will need every bit of that vitality in the days ahead.

IV. Recent Advances in Reactor Technology

The technology of reactors has progressed considerably in the last couple of years. Much of this progress is in areas covered by security regulations. But even leaving these areas out, there is a great deal to say about the current crop of reactor experiments and of experimental reactors.

I use the two distinct terms "experimental reactor" and "reactor experiment" advisedly, for, as the technology unfolds, it has become more and more clear that a distinction exists between reactors built as pilot plants (reactor experiments) and reactors built as neutron sources for general scientific exploitation (experimental reactors).

That pilot plants are necessary in a technology as bizarre as nuclear energy might seem to be a commonplace, but partly because the Hanford reactors were successfully built essentially without a pilot plant, and partly because a deeply essential characteristic of a reactor—its power per unit volume—can be realized only in a full-scale system, it had been customary to circumvent small protoype reactors in proceeding to a full-scale system. This trend has, I think fortunately, been reversed, and two pilot plant reactor experiments, the Experimental Breeder Reactor and the Homogeneous Reactor Experiment, have been constructed in the last two years. Both these reactors, which are in the 1000-kw class, are much smaller than their ultimate embodiment. Although their small size makes them incomplete pilot plants, they do have enough in common with big-scale breeders or homogeneous reactors to make the experience gained with them enormously relevant.

EXPERIMENTAL BREEDER

EBR has already been described in considerable detail.* It is a pilot plant for a fast-neutron breeder, and therefore contains no moderator and is, in consequence, extremely small. That a breeder should operate on fast-neutron fission rather than on slow-neutron fission is suggested by the manner in which the fission-to-capture ratio in U^{235} varies with energy.

Capture of a thermal neutron by U^{235} leads to fission (with a yield of 2.5 neutrons per fission) about 83% of the time and to radiative capture (with a yield of no neutrons) the remaining times. Thus when a U^{235} nucleus is destroyed by thermal fission, only about 2.14 new neutrons are released. For fast neutrons, η, the number of neutrons produced per U^{235} destroyed, is substantially larger than 2.14. The feasibility of breeding thus depends very sensitively on $\eta - 2$, the breeding gain, since one neutron is needed to maintain the chain and one neutron is needed to make a new fissionable nucleus to replace each destroyed one; and it is natural to look toward fast reactors which have high breeding gain for success in breeding.

EBR, being nonmoderated and therefore very small, requires the very best heat transfer medium if specific powers

*W. H. Zinn, Nucleonics 10, No. 9, 8 (1952).

of reasonable magnitude are to be achieved. The actual coolant used in EBR is NaK eutectic which melts at 12° F and boils at 1500° F. The operating temperature of EBR, 660° F, is rather modest but is sufficiently high to produce 400-lb steam. This steam is now being used routinely to produce about 150 kw of electricity—the first electricity from nuclear fission.

HOMOGENEOUS EXPERIMENT

The other reactor experiment which is just getting underway is HRE at Oak Ridge. This system consists of an aqueous uranyl solution which operates at sufficiently high temperature, and therefore pressure, to produce steam which runs a small turbine.

The reactor is water-moderated and is therefore a thermal reactor. As a potential breeder, with D_2O replacing the H_2O, it would suffer by comparison with the nonmoderated EBR; the value of η for U^{235} would be only about 2.14. However, the heat produced in this reactor is transferred by actually circulating the fluid fuel round and round through an external heat exchanger, and this relatively efficient heat transfer method makes possible much higher specific power output, i.e., power per gram of uranium, than is attainable in EBR. Thus the turnover rate of the fuel is potentially much higher than in a fast breeder, and it is hoped that the yearly interest rate on the fuel, which is proportional to specific power times breeding gain, might be competitive with the yearly interest rate in a fast breeder, which has higher breeding gain but lower specific power.

Perhaps the most interesting physical questions in an aqueous circulating fuel system are connected with its stability. By virtue of its fuel circulation, such a reactor loses many of its delayed neutrons. Since the delayed neutrons tend to lengthen the time scale of the reactor, it would be supposed that their loss might seriously compromise the stability of the system against small fluctuations. Although, in general, this is true, this effect is balanced in an aqueous system operating at high temperature by the fall in density and in H_2 scattering cross section as the temperature rises. On both these counts the leakage of neutrons from the system increases as the temperature goes up, and this gives the reactor a strongly negative temperature coefficient, as much as $-10^{-3}/°$ C.

The kinetics of such a "no-delayed-neutron" reactor into which an increment of reactivity, δC, is suddenly introduced, is easily deduced, as shown by J. Stein (Westinghouse), from the reactor's "equations of motion." These are, for power removal at a constant rate, P_0,

$$dQ/dt = SdT/dt = P - P_0$$

$$dP/dt = [(\delta C + \alpha T)/l]P$$

where Q is the heat content, S is the heat capacity of the reactor, α is the temperature coefficient of reactivity, l is the generation time, and P is the power at time t. This pair of nonlinear equations can be discussed most easily by writing the differential equation of the phase diagram

$$dP/SdT = [(\delta C + \alpha T)/l(P - P_0)]P$$

which, on integration, gives

$$\frac{P - P_0}{P_0} - \ln \frac{P}{P_0} = \frac{S}{P_0 l}\left(T\delta C + \frac{\alpha}{2}T^2\right)$$

The reactor is seen to undergo relaxation oscillations, provided α is negative; if α is positive, the reactor is unstable. The maximum temperature excursion is

$$T_{max} = -2\delta C_0/\alpha \qquad (1)$$

This excursion is just twice the excursion, $|\delta C/\alpha|$, which would reduce the reactor to the just-critical state. Equation 1 means that even if 1% excess reactivity is inserted into a reactor which has *no* delayed neutrons, but for which $\alpha = -10^{-3}/^{\circ}$ C, the maximum temperature rise is only about 20° C.

The delayed neutrons damp the oscillations. This is seen most easily for the case of small oscillations. Without delayed neutrons these oscillations are sinusoidal with period

$$t = 2\pi \sqrt{lS/|\alpha|P_0}$$

The delayed neutrons damp the oscillations with a damping constant $2l/\beta$, where β is the fraction of delayed neutrons.

Thus, as long as the temperature coefficient is negative and large, circulating fuel systems seem to be stable; or, at least, oscillate with finite amplitude. Because of the very strong coupling between reactivity and temperature, such reactors are inherently self-regulating. Any increase in power demand (as for example, opening the steam throttle, i.e., cooling more efficiently) tends to cool the inlet fluid to the reactor; this increases the reactivity, which increases the power. This raises the outlet temperature until the extra reactivity is balanced by a restoration of the original temperature profile. To change the temperature of such a strongly coupled system, only the control rod need be moved. If the reactivity is reduced, the system temperature will fall until the loss in reactivity is restored by the lower temperature.

EXPERIMENTAL REACTORS

With this very quick resumé of the status of our reactor experiments I now turn to the new experimental reactors—the neutron sources. In this country we are particularly fortunate for possessing the U^{235}. Since enriched reactors are small we can, on this account, make extremely intense reactor neutron sources with relatively modest-scale devices. This philosophy underlies the Los Alamos and North Carolina State College water boilers, both of which run at less than 50 kw yet achieve a flux comparable to the flux in the huge Oak Ridge or Harwell graphite reactors. It also underlies the most advanced experimental reactor ever built—the Materials Testing Reactor—as well as its daughter, the Low Intensity Test Reactor.

MTR was designed and built as a joint enterprise of the Oak Ridge National Laboratory and the Argonne National Laboratory. It is located at the Reactor Testing Station, Arco, Idaho, where it is operated by the Atomic Energy Division of the Phillips Petroleum Company. It is now the major irradiation facility of the Atomic Energy Commission. LITR was originally a hydraulic mockup of the MTR and was converted into a nuclear reactor at ORNL in 1950.

In designing a reactor radiation source it is desirable to maximize both the fast-neutron (> 1 Mev) and the thermal-neutron flux. If maximum slow-neutron flux is desired, then, since power output in a reactor is proportional to fission rate,

$$P = N\sigma_f\Phi_{th}$$

or the thermal flux, Φ_{th}, is

$$\Phi_{th} \sim P/N$$

where N is the number of U^{235} atoms per cubic centimeter, σ_f is the thermal fission cross section, and P is power per cubic centimeter. Thus the thermal

flux is proportional to the power per kilogram of uranium.

To achieve maximum thermal flux it is therefore necessary to maximize the heat transfer from each gram of uranium fuel. This is automatically accomplished in a homogeneous reactor, and it implies in a heterogeneous reactor that cooling *surface* per gram of uranium be as large as possible.

To maximize the virgin or uncollided flux it is necessary to maximize the power per unit volume of reactor. The uncollided flux of neutrons, Φ_0, is

$$\Phi_0 \Sigma_s = q$$

where Σ_s is the macroscopic scattering cross section; q is the number of neutrons produced per cubic centimeter per second and is therefore proportional to the power per unit volume, P. Thus

$$\Phi_0 \sim P/\Sigma_s$$

or, since Σ_s at high energy is rather insensitive to the kind of moderator, the virgin flux is proportional to the power per unit volume.

Thus, to build an experimental reactor which maximizes both the slow and the virgin fast-neutron flux it is desirable to extract as much heat as possible from a given amount of uranium, and at the same time to keep the reactor volume as small as possible. Both conditions are met automatically in an aqueous homogeneous reactor. However, the chemical engineering problems involved in running aqueous systems at high nuclear power are so formidable that it was deemed best to make such a maximal neutron source with a heterogeneous reactor.

One solution to the problem of designing a heterogeneous reactor as a maximal neutron source is that used in the Swimming Pool Reactor.* In this reactor, the heat transfer area per gram of uranium is maximized by disposing the U^{235} in a thin plate; volume is minimized by using the same water for moderating and cooling. A stack of 20 fuel elements is immersed in a pool of water. The fuel elements consist of thin parallel plates of aluminum sandwiches with an enriched uranium filler as the "meat" of the sandwich. The plates are spaced at intervals of a few millimeters, and this space is used by the water both to cool and to moderate. The control elements consist simply of cadmium rods which move up and down in unused fuel-element spaces.

A reactor of this sort is extremely flexible; many different fuel loadings are permissible, and in this way the intensity and the spectrum of the flux at the experimental ports can be changed at will. The Swimming Pool Reactor is cooled only by natural convection. It normally operates at about 100 kw, at which power, since the critical mass is about 3 kg of U^{235}, the average slow neutron flux is about 10^{12} n/cm²/sec.

LITR and MTR are also heterogeneous, light-water cooled and moderated, enriched-uranium reactors designed for maximum neutron source characteristics. LITR provides an average thermal neutron flux greater than 10^{13} n/cm²/sec, whereas MTR provides an average thermal neutron flux greater than 10^{14} n/cm²/sec. In MTR the maximum neutron intensity available in a beam hole is over twice the average flux. Both reactors have power levels measured in megawatts.

I suppose it is fair to say at this time that one of the pleasantest surprises of the postwar nuclear energy development has been the extraordinary reliability with which MTR operates. This is particularly significant since it

*William M. Breazeale, Nucleonics 10, No. 11, 56 (1952).

demonstrates that very high power density—hundreds of kilowatts per liter for MTR—in itself is not prejudicial to the success of a nuclear reactor.

There are two nuclear characteristics of MTR—the shutdown behavior of the reactor and the neutron buildup in the reflector—which are of interest. As is fairly well known by now, Xe^{135}, a 6% yield fission-product daughter of the 6.7-hr I^{135}, has a slow-neutron cross section of 3.5×10^6 barns. In a reactor running at a flux of 10^{14} n/cm²/sec, the half-life of Xe against neutron capture is about ½ hr, whereas, the natural lifetime of Xe^{135} against beta decay is about 9.2 hr. Thus in MTR, nearly every Xe^{135} atom formed absorbs a neutron and the reactivity of MTR gradually decreases as the Xe^{135} builds up by decay of its parent I^{135}. This reactivity loss saturates at about 4.5%, this being the product of the fission yield by the fraction of neutrons which go into fission.

After the reactor is shut down, the I^{135} continues to produce highly absorbing Xe^{135} atoms; however, because there are now no neutrons to destroy the Xe^{135} its concentration will rise and will continue to rise until the natural decay of the Xe^{135} overbalances the decay of the I^{135}. Thus a reactor whose thermal flux is 10^{14} n/cm²/sec will undergo a great decrease in reactivity after shutdown, and after about 10 hr, when the Xe^{135} concentration is at its maximum, the reactor will have lost as much as 20% in reactivity. This means that a few hours after a high-powered reactor such as MTR has been shut down, it is impossible to start it up again unless considerable excess reactivity is built into it, or unless new fuel which contains no Xe^{135} is placed in the reactor, or unless sufficient time is allowed for the Xe^{135} to decay.

The other design characteristic of these small thermal reactors has to do with a method of artificially increasing the thermal-neutron flux in the reflector which surrounds the experimental beam holes. Since the life-time against capture of a thermal neutron in a Be or BeO reflector is very much longer than it is in the highly absorbing reactor, the thermal-neutron density tends to build up in a slightly absorbing reflector. In this way it is possible to increase the thermal flux in some parts of the reflector of MTR. This of course is valuable to experimenters who need the highest flux in the region outside the reactor.

COMMERCIAL POWER

This account of our reactor experiments and of our experimental reactors would be incomplete, as is any article on atomic energy, without some observations on why we don't now have commercial atomic power on a big scale. To add my ideas to all the others that have sought to answer this complicated question, I shall make only this technical, not political, observation: commercial power technology is basically a conservative technology, it depends for its economic success on small profits in large units over very long times. Thus, successful commercial steam prime movers must be devices which last a long time, say 20 yr, whereas the only *experimental* nuclear electrical producers, EBR and HRE have produced electricity for only one year, and less. The lifetime of any high-temperature device is limited by the integrity of the materials. Even without radiation, prediction of how long any such device can last is at best risky, and there is no substitute for time in getting a reliable estimate of longevity. So it is that one of the central

reasons we can go only so fast in achieving successful large-scale commercial nuclear power is that we cannot predict with confidence how long our nuclear-producing gadgetry will last. Questions like this naturally lie in the province of the solid state physicist and metallurgist.

With magnificent radiation sources such as MTR available, I think that we can now embark on the time-consuming, but ever so necessary job of finding out, instead of guessing, how long we can expect materials to hold up in the strange and exacting environment which they encounter in a high-temperature, high-radiation reactor. Only when adequate answers to these questions are available can we hope to achieve a full-scale nuclear power enterprise that is competitive with ordinary power sources.

TRANSISTORS

CLARENCE KABELE

The Author

Clarence Kabele is an oldtimer who was born with an insatiable curiosity regarding "the nature of things." Lacking opportunity for extended education due to the death of his father he was forced to employ toilsome (and sometimes unorthodox) private study projects to overcome the deficiency. Perhaps this tendency to a "grass-roots" approach is reflected in the article.

During a varied career he has been a Switchboard Design Specialist with General Electric, a Building Electrical Engineer with New York State, an Electrical Engineer both with Treasury Dept. and the Bureau of Yards and Docks, and, at present, Supervising Electronics Inspector at the Office of Inspector of Machinery, USN and Naval Inspector of Ordnance, Schenectady, N. Y.

Editor's Note

The article was made available to the Journal by Captain E. C. Forsyth (USN), then incumbent Inspector for whose use Mr. Kabele had prepared it. Possibility of publication had not been considered by the author because of his opinion that it lacked literary style. Neither Captain Forsyth nor the Editor shares in this modest evaluation.

Within recent years a new electronic amplifying device known to the trade as a transistor has been advanced as a possible replacement for the more familiar vacuum tube. So intense has been the drive to market these devices that many persons who occupy executive positions and whose knowledge both of electronic theory and terminology is meager at best now are faced with the necessity of making far-reaching decisions in the field of this tube-versus-transistor conflict. So long as tubes alone were involved the choice lay simply between tube types. However, transistors are very different from vacuum tubes in departments such as construction, function and limitation.

Thus the expanding art of electronics is pressuring procurement officials into the realization that, in some measure at least, its functions and problems require to be understood. The average man not specializing in this field who attempts to investigate has a tendency to feel utterly lost amid the unfamiliar.

Perhaps this situation need not continue indefinitely; perhaps the inherently simple ideas underlying electronic functions might be made understandable if translated into more commonly understood media.

The following is an attempt to bridge this gap by means of an informal presentation of the functioning of two

electronic amplifying devices in concepts akin to the primer rather than the text-book. No apology is offered if the subject matter appears to be unorthodox in representation. The following is not written for the specialist.

A three-element (triode) vacuum tube (or "valve" as the British call them) when used as an amplifier of electronic impulses is functionally a valve in every sense of the term. It works in a manner similar to the steam valve or the hydraulic valve except that it controls the flow of a stream of electrons instead of water or steam. An hydraulic valve, for example, has an opening in one end where fluid under pressure enters, flows through a gate in the middle, and runs out at the other end. A vacuum valve has a hot cathode from which electrons under electrical pressure are released, flow through a gate (or "grid") and out through the anode at the other end. The hydraulic valve has a mechanical gate which can be seen to open or close when regulating the internal flow of fluid. The vacuum valve has a meshwork of wires (the grid) which performs as a gate: a negative electric charge impressed upon it will cause the wires to increase in diameter (electrically, that is) until the meshwork thickens and closes up solid; while a positive charge will cause the meshwork wires to become (electrically, of course) increasingly thin until they actually disappear as far as offering impedance to the electron flow. This apparent change in wire diameter cannot be seen by a human observer, but it is very real to the electrons. Thus the "gate" action of the compared valves is identical as far as results go.

When James Watt built his first steam engine he attached two cords to the control valve: one of them when pulled was to open the valve and admit steam to push the piston forward; the other when pulled was to close the valve and permit the piston to retract. Properly timed, this ebb and flow of steam in the cylinder enabled the engine to generate power; a small boy, by pulling the cords alternately, could get a lot of work done.

A similar feat may be accomplished when using the vacuum tube as an amplifier: two electrical cords (positive and negative) are operated by a small boy (the input) to open and close the gate (grid) of a vacuum valve. The resulting ebb and flow of electrons through the pipes (in this case wires or cables) can generate enough power to spin gun-turrets around. Of course it is not necessary nor desirable that all this happen in a single valve. One valve may operate another in cascade until the power build-up is sufficient.

A small boy really was given the task of pulling the cords on Watt's steam engine. Tiring of this monotonous labor he hit upon the trick of rigging the cords to the moving piston in such fashion that the engine went into oscillation and kept itself running. At a much later date an American boy, Doctor Lee DeForest, successfully did the same thing to a vacuum tube. Ordinarily we do not associate an oscillating vacuum tube with a reciprocating steam-engine, but, functionally, they have this in common: the slide-valve gear on one has its virtual counterpart in the positive feedback gear on the other.

Another trick in use today is one that the small boy never dreamed of. The final output from a series of vacuum tubes operating in cascade may differ widely in wave-shape from that of the input wave shape. This is called distortion and is caused by the inability of electronic devices in general to repeat things precisely as they are told. As a remedy we may divert part of the final output and hook it up to a more forward tube through an electronic slide-valve gear working in reverse. This will flatten our amplification gain right down, but also it will iron out nearly

all of the distortion. This trick commonly is called "negative feedback" to distinguish it from the more common "positive", or oscillation-producing feedback.

Now we are ready to approach the subject of transistors, proper, and we will consider a three-element junction-type of the p-n-p variety. Since transistors are being proposed as replacements for vacuum tubes we might well imagine that one could present the transistor as a simple valve and get it over with. But each variety of transistor is composed of a solid block of material with no hole in the middle to place a control gate in. However, if it is capable of replacing the tube at all it must function as a valve of some sort; therefore SOME means must be devised for regulating the flow of electrons through it other than the application of electrical pressure at each end. Practicable means to effect the equivalent of this required valve action have been discovered and are being utilized, but they are far from simple. In order to convey even a foggy idea as to how it is done we must resort to further analogy.

Since we now are dealing with a solid let us imaginatively represent a fragment of this solid as a company of soldiers. We picture the soldiers of the assembled company as being spaced wide apart in smart formation at Present Arms. (These soldiers might represent the crystal lattice of a bit of copper wire.) Suddenly a horde of intruding soldiers appear and rush through the ranks of the assembled company. (This represents an electric current flow.) There is room for a large influx of runners to stream through the parallel lanes, but some of the company soldiers are knocked around and get hot about it (as does the bit of copper wire). Finally, if enough intruders come smashing through, the company will become entirely disorganized and its formation destroyed. (Burned-out is the word.)

Another company who is inclined to resent such rude intrusion takes measures to prevent it. Its members form into clumps and hold each other's outstretched hands. Intruders might squeeze into the front lines but can penetrate no farther. (This represents an insulator). But now the weather suddenly gets unbearably warm and under its influence the soldiers rapidly lose discipline, relax their handholding and no longer resist being transferred in or out. (This represents an intrinsic semi-conductor such as germanium.) How warm? Room temperature is enough for germanium.

Suppose a horde of intruding soldiers endeavors to rush through this kind of a company. Here are no wide-open lanes through which one can sail like a bowling ball. After the intruders have penetrated the front ranks they must twist and turn and bounce ("diffuse") through a tortuous labyrinth before ever they reach the rear. So not too many of them get through. (They meet with "limiting resistance".) However this particular company does not differ in type from those representative of insulators and semi-conductors.

Thus far we have scouted the ground for general possibilities only. We have progressed to the point tubes had when they were electric lamps. The first significant phase in vacuum tube development turned out to be the two-element rectifier. Let us see if, somehow, we can't duplicate this step with semi-conductors as the diode elements.

We might start with the idea that some particular form of germanium could conduct electrons more readily in one direction than the other. (So far no such material has been uncovered.) Then we might try and see if two differing forms of germanium, perhaps placed back-to-back, could accomplish rectification at the junction area. Here we strike pay-dirt.

To understand what steps come next we return to our company of soldiers

analogy. Thus far we have needed to consider only the soldiers (electrons), but now we find this to be too simplified and so we must stretch it a bit to include the atomic nucleii. These atomic nucleii are the creatures which hold both themselves and the electrons in place in a molecular structure; so we may just picture them as creatures with multiple hands and this will suffice.

In the case of pure germanium these creatures each possess four hands (valence bonds), two of which they use to cling to adjacent creatures and two with which to latch onto soldiers (electrons). (NOTE: This is a boiled-down version of a highly complex crystal lattice structure. While it preserves the essential facts of transistor operation still, to a physicist it presents a most incomplete and unsatisfactory picture.) Taken all together this forms a nice snug structure, not wide open like the conductors nor buttoned-up tight like the insulators.

Since, as we have seen, a single uniform structure will not suffice to accomplish rectification, we must somehow transform this pure germanium into at least two other forms more suitable for use.

Now by means of divers arts we adulterate ("dope-up") one of these pure germanium companies and inject into their midst a sprinkling of five-handed creatures (phosphorus, antimony or arsenic). This results in the addition of more soldiers to the company, they being attached to the extra number-five hands. If we attempt to pass an influx of intruding soldiers through this company their progress is accelerated by the presence of the extra hands to help swing them along on their journey. Just cram a soldier into an end of this company and one is cheerfully tossed out at the other end.

These five-handed creatures are known as "donors": they will donate soldiers at the drop of a hat to any cause whatever. We name this impure form of germanium n-type ("never refuse to welcome a soldier"). It operates best when filled with excess soldiers shoved in under pressure.

Next we take another pure company and dope it up with a sprinkling of three-handed creatures (aluminum, gallium or indium). These fellows work at a disadvantage from the start. First, the entire company always is chronically low on soldiers; second, the ranks are full of gaps ("holes") where soldiers should be standing were there sufficient hands to retain them. When an influx of intruding soldiers attempts to traverse this company they get little assistance from these short-handed creatures who stand ineffective to render aid. Increasing the pressure does not help much. But if, instead of pushing soldiers in, you pull them out of the front ranks (by employing an electronic suction effect known as a "positive electric charge") then this company will accept recruits from the rear and will pass them along eventually to fill the "holes" caused by the vacuum in the front ranks.

These three-handed creatures are known as "acceptors". They have nothing to donate; when you forcibly remove a soldier from the ranks they will accept another for ultimate replacement.

(Here we digress a moment to startle the military mind. Military men have seen soldiers marching up and soldiers marching down, but never in the you-know-what have they seen a "hole" marching! But they will; scientists have it all taped out.)

This impure form of germanium we call p-type ("positively no additional recruits"). It operates best when a soldier deficit condition exists in the ranks.

When considering the p-type company we discover that natural gaps in

the ranks occur whenever a three-handed creature stands, due to its lack of a fourth hand to retain the soldier needed to maintain symmetry. These natural gaps are, as it were, dead holes which tend to remain so. But when, under electronic suction, a hole is formed where a soldier has been pulled away from a four-handed creature, then this hole is very much alive; it is subjected to great pressure urging it to get filled.

When a live hole is created in a front rank a soldier from a rank rearward is yanked forward into the vacancy, only to leave another live hole in place of the original. This chain-reaction of "hole-hopping" occurs and keeps up as long as voltage is applied across the p-type germanium. It impels soldiers to move by steps from rear to front, and the "holes" appear to move, progressively, from front to rear. Screwy as it sounds if we will concentrate upon the hole motion here instead of on the soldier progression we may simplify our thinking in regard to the overall picture: in the n-type company the soldiers move from front to rear; in the p-type company the holes move from front to rear. When they meet, soldier pops into hole, fills it up and relieves the pressure.

Finally we have reached a stage where we may assemble one company each of the "p" and of the "n" types, place them back-to-back and expect to obtain "polarized" results. To do so we connect our electric circuit so that extra soldiers (electrons) are pushed into the front ranks of the "n" company, and a deficit of soldiers is created in the front ranks of the "p" company. In the "n" company the soldiers stream rearward, happily; in the "p" company, as soldiers hurry to fill in gaps up front, the new-formed "live" holes stream rearward where, at the junction border, soldiers and holes merge. This is real electric current flow and, being in a natural (forward) direction, may be accomplished with the application of but small pressure (voltage).

This goes so well that we try reversing the process. We run into trouble immediately. Extra soldiers pressured into the front ranks of the unfriendly "p" company bog down in their march rearward. Gaps caused by removing soldiers from the front ranks of the clutching "n" company are filled most reluctantly. The companies swiftly are drained of mobile soldiers and holes, and at the junction border an ever-expanding desert develops, denuded of active life. Current in this direction of flow dwindles to a trickle right away. By increasing the pressure (back voltage) we can force the issue to some extent, but flow is in the direction of greater resistance.

We have achieved our first objective; a pair of these companies will make a most elegant rectifier. But so far no trace of valve action is apparent so we must readjust our sights.

Fate finally took a hand in uncovering the essential clue. Quite by accident the trick was discovered at the Bell Telephone Laboratories. While experimenting with a "whisker" type germanium rectifier, someone placed another whisker close to the original one and disclosed the surprising fact that a current through the second whisker could be made to modulate the original current flowing through the first whisker. Thus the prototype of the transistor was born. Let us consider the modus operandi.

Translated into our terminology we set up two companies (p & n) back-to-back and apply a high voltage in the direction of greater resistance (back voltage). A comparatively small current will flow in spite of the scarcity of mobile soldiers and holes at the junction. If, by additional means, we could flood this border area with a supply of

easily obtained soldiers or of holes we could break the bottleneck and increase the current in the back voltage circuit. This would accomplish an equivalent of opening the gate of a valve.

Although we are offered a choice let us follow in the footsteps of the original experiment. We will add a third (p-type) company to our regiment, making of it a p-n-p sandwich. Now to perform the trick: we set up a small "forward" pressure (voltage) between the newly-arrived "p" company and the original "n" company. (This is additional to the original circuit between the older "p" company and the "n" company.) What happens? The new "p" company obliges with a flood of holes, more than enough to supply the new circuit. And there, looming across the ranks of the uncooperative "n" company, stand fidgety soldiers in the original "p" company who desperately need these newly-formed escape hatches. If the "n" company be made thin in formation, like a slab of bologna in the p-n-p sandwich, then the soldiers can burst across the thin dimension of the "n" company, seize upon the now reachable holes, and thus by-pass the long road home. This heaven-sent opportunity spells additional current flow for the high voltage circuit even if it does appear not to happen according to Hoyle.

Thus at the expense of supplying a small "forward" voltage with its accompaning current we easily can more than double the current in the back voltage circuit. This, you say, is not true valve action? Who cares; it is the EQUIVALENT. How come that a "p" company can be so over-generous in supplying holes? Somehow it is possible; it works.

Conversely we can construct an n-p-n sandwich of companies. The new "n" company gladly will accept a flood of invading soldiers to pour across the thin-dimension borders of the "p" company, and thus steer clear of the far trail down through unfriendly "p" company territory.

Here we have the case of an electric current flow which provides the means of increasing the current flow in another circuit without, for itself, requiring additional power. The end result is current flow modulation of current flow, very different from the action of a vacuum tube where a voltage (operating the grid) modulates current flow through the tube. For this reason a transistor seldom can directly replace a vacuum tube in an electronic circuit. Of course it can perform functions (amplification, oscillation, etc.) equivalent to those performed by a tube, but it performs them in a significantly different manner.

* * *

Readers who have attempted to follow current transistor literature will wonder why so many identifying terms seem to have been omitted. Point-contact (whisker) type rectifiers and transistors both preceded the junction types. While electronic functions are much easier to follow when considering the junction type, terminology pertaining to point-contact devices is the language in present usage, and this can become very obscure when transferred directly without benefit of translation.

The three-element point-contact type transistor consists of: (1) a piece of germanium (n-type) called the block; (2) a high (back) voltage contact point called the collector; (3) a low (forward) voltage contact point called the emitter. The high (back) voltage circuit is connected to the block and to the collector point. This whisker tries to "collect" enough "holes" to satisfy the electrons that the back voltage endeavors to push through it into the block. Push as it will this current remains small.

The low (control) voltage circuit is a separate one connected between the block and the emitter point. This whisker, when passing current, "emits" excess "holes" which enter the block (by "hole injection") and migrate directly to the "collector" where they absorb additional electrons from the whisker point and thus increase the flow of collector current.

The current amplification function of a transistor is given in the form of a ratio kown as "Alpha". It is the ratio of the increase in emitter current (starting from zero) to the increase in collector current (starting from the original collector current at zero emitter current). If one milliampere of emitter current will add one ma. to the collector current, then Alpha is 1.0 or unity. If one ma. of emitter current adds two ma. to the collector, then Alpha is 2.0 or twice. If one ma. of emitter current adds one-half ma. to the collector current, then Alpha is 0.5 or one-half. In point-contact transistors Alpha customarily exceeds unity; in junction types it amounts to unity or less.

* * *

When engineers cognizant of fields other than that of Electronics endeavor to follow the meanderings of current flow in the transistor they collide with flow concepts which seem foreign to logical thought. The very idea of a flow that employs the subterfuge of empty spaces (holes) moving one way when the real particles (electrons) move the other appears repugnant to say the least. Assuming, with good reason, that they are sane men, what bundle of catnip could induce the Electronic Brethren to indulge in such odd thought-patterns? Because of these thought-patterns, and similar ones of their ilk, there has long been a serious barrier to any free or easy exchange of basic ideas between Electronic and other Engineering branches.

The fundamental dilemma can be pinned down to within the range of one single consideration: the behavior patterns of positively-charged atomic particles. The positively charged particle, or ion, is an atom with one or more of its outer electrons knocked off. It is a frightfully massive thing compared with an electron. The tiny electron, or negatively charged particle, can slip elusively anywhere between the great atomic spacings; for practical purposes it is almost equally mobile in any medium: solid, liquid, gaseous, or in a vacuum. But the poor positively charged oafs get in their own way. In a gaseous medium they fly about banging into everything. In a liquid medium they crawl about getting into chemical messes. But in a solid they are constrained to stay put, chained by one leg in migrant immobility.

Without trying to blanket the general case let us consider their activity in the tube-versus-transistor dilemma. For a half century at least electronics workers have divined and calculated the epic of the running battle between electron and ion within the vacuum tube. They have watched streams of darting electrons hammering anodes into incandescence; they have observed the consequences of the vicious battering inflicted by mobile ions when raining down upon the roof of the cathode; and, out in deep space in the thyratron or the neon sign, they have witnessed jet-propelled electrons knocking the Northern Lights out of dogged squadrons of ions. Always the streams of positives and negatives flying at each other's throats; the ceaseless flow of both-ends-against-the-middle, unmatched and unparalleled in any other Engineering field.

For over half a century, then, tube men watched and estimated this two-way flow. They amassed a priceless wealth of concepts and of mathematics wherewith to bring the fairy possibilities of the electron into the range of practical

efficiencies. Then came the transistor, a solid, that eliminated one ambulant member of the dual-flow team. The fettered ions were out of this flow picture now, and so might be the hard-won concepts and mathematics which had conquered the kingdom of the vacuum tube. In this hour should the possibility of the correlation of tube-transistor functions be thrown overboard simply because stubborn fact intervened?

Dr. John S. Saby summarized the outcome in simple terms: "Since the holes move in the opposite direction to that of the electron in an electric field, they can be regarded for some purposes as positive charges. This is called p-type conduction."

ATOMIC PROPULSION–WITH SPECIAL REFERENCE TO MARINE PROPULSION

ACKNOWLEDGMENT

This article, written by SIR JOHN COCKCROFT, has been excerpted from the April 1953 issue of the "Transactions of the Institute of Marine Engineers". It was based on a lecture given before the Institute.

INTRODUCTION

On 14th June 1952, the President of the United States launched the hull of the first nuclear propelled submarine. In doing so he said, "We are assembled here to lay the keel of a navy submarine, the USS *Nautilus*. This ship will be something new in the world. She will be atomic powered. Her engines will not burn oil, or coal. The heat in her boilers will be created by the same force that heats the sun—the energy released by atomic fission, the breaking apart of the basic matter of the universe . . . The *Nautilus* will be able to move under the water at a speed of more than twenty knots. A few pounds of uranium will give her ample fuel to travel thousands of miles at top speed. She will be able to stay under water indefinitely. Her atomic engines will permit her to be completely free of the earth's atmosphere. She will not even require a breathing tube to the surface. The military significance of this vessel is tremendous. The engine of the *Nautilus* will have as revolutionary an effect on the navies of the world as did the first ocean-going steamship 120 years ago. The power plant that will go into this submarine is not just being planned on paper. The Atomic Energy Commission and the Navy have actually gone out and built a submarine hull on dry land at Arco, Idaho. They are putting into it a full-size, working engine, complete in all respects—the same kind of engine that will be used in this ship.

That engine on dry land is almost complete right now. Soon they will start it running and give it the most thorough tests. And, believe it or not, when they are through working with that model it will be perfectly possible to hitch it up to turn out electricity, like any other dry land power plant".

The United States has, during the last few years, made a number of other statements about their nuclear propulsion program. Three projects are proceeding. The first is being undertaken by the Westinghouse Company in collaboration with the Argonne National Laboratory; the second is being undertaken by the Knolls Atomic Power Laboratory of the U. S. General Elec-

tric Company. A third is to develop a nuclear propulsion unit for an aircraft carrier.

It is natural, therefore, that interest should develop in marine engineering circles on the potentialities of this new form of propulsion. I have undertaken the task of delivering this lecture with some misgivings—first, because these developments are in a very early stage, second, because we have been prevented from devoting effort to marine propulsion by shortage of engineering resources and, third, because detailed technological information is classified. I must, therefore, limit myself to a very general account of the subject.

PRINCIPLES OF NUCLEAR REACTORS

Nuclear propulsion will make use of nuclear reactors as a *source of heat* to replace the oil burning or coal burning equipment of conventional power units. A nuclear reactor is an assembly of uranium with other suitable materials in proportions such that a nuclear chain reaction in uranium can develop. Uranium nuclei are then split up in large numbers, releasing energy in the form of kinetic energy of the fission fragments, in neutron energy and in gamma ray energy. This "high temperature" energy is rapidly degraded to heat energy and heats up the uranium metal and other materials of the reacting core (Fig. 1).

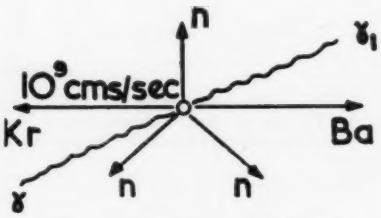

Fig. 1. Energy release in fission

Kinetic energy of fission fragments	178 million volts
Kinetic energy of neutrons	5 million volts
Energy of gamma rays..	5 million volts
Radioactive energy of fission fragments	8 million volts

The simplest type of reactor uses fuel rods of uranium in its natural proportions of one part of light uranium—U-235—to 140 parts of heavy uranium—U-238. The fuel rods are surrounded by a medium, such as heavy water or graphite, which serves to slow down the neutrons given out in the fission process to speeds at which they are most effective in producing further fission. Reactors have a minimum or critical size below which the chain reaction will not develop. This consists of about three tons of uranium metal in about five tons of heavy water; or about 20 tons of uranium metal in 650 tons of graphite.

This can best be understood by considering the neutron balance sheet of the reactor which is shown in Table I.

The fission of a U-235 nucleus releases on the average 2.50 neutrons. As the neutrons pass through the uranium metal fuel rods they have a small chance of producing further fissions whilst they are moving fast. This increases slightly the neutrons available. One of the neutrons is required to carry on the chain reaction. Some of them are captured in U-238 to produce U-239, which then changes to a new fuel atom—plutonium. Others are captured in the graphite or aluminum sheaths of the uranium rods and some escape. The chain reaction can only start if there is a slight positive neutron balance. We call this the excess reactivity, or excess K, of the reactor.

We can now see the reason for the critical size—for if the reacting core is too small, the proportion of the initial neutrons escaping from the core will be

TABLE I—APPROXIMATE NEUTRON BALANCE SHEET FOR GRAPHITE PILE

Neutrons per fission of U-235	2.50
Fast fission neutrons from U-238	0.06
Total neutrons from fission	2.56
Absorbed in U-235 to produce further fission	1.00
Absorbed in U-235 to produce U-236	0.20
Absorbed in U-238 to produce plutonium	0.90
Absorbed in moderator	0.30
Absorbed in other materials	0.05
Escaping from core	0.09
Excess neutrons δK	0.02
	2.56

larger and there will be a neutron deficit in the balance sheet. We can also see that if we increase the absorption of neutrons in any other line of the balance sheet we must decrease the proportion of neutrons escaping—in other words, the critical size goes up. If, for example, the engineers use more aluminum to sheath the uranium rods or if they substitute steel for aluminum this follows.

The proportion of neutrons absorbed wastefully in uranium and moderator increases with temperature. High temperature operations thus require a greater size. Neutrons are also absorbed in the waste products of fission —the nuclear ash. These are called "reactor poisons". The principal poison is the rare gas—xenon 135—which has a very high absorption for neutrons. This poison is radioactive—it decays by a factor of 2 in every 9.4 hours. The amount formed at a given power level builds up until the amount being formed equals the amount decaying. So the amount of poison increases with the power level. The reactor must, therefore, have sufficient initial excess K to provide for this poisoning.

The heat which can be developed in the reacting core is limited mainly by two factors: first, the amount of excess K available initially; second, by the heat removal capacity of the coolant, in relation to the maximum safe temperature of operation of the fuel elements.

The intensity of the chain reaction—the number of uranium nuclei splitting up per second—and with it the amount of heat developed is governed by control rods which are moved into and out of the reacting core. These control rods contain boron and absorb neutrons strongly. When they are fully inserted the neutron balance is heavily negative. To start up the chain reaction they are withdrawn until the excess reactivity is about 0.0001. The chain reaction will then build up exponentially with a time constant of about 63 seconds. The time constant varies as $\frac{1}{(K-1)}$ so that it is undesirable to provide too much excess K and the control rod withdrawal motion is usually limited to slow speeds.

When the reaction has reached a desired level, the control rods are moved in again to make $K = 1$. Fig. 2 shows the course of the reaction in a typical operation.

The amount of the U-235 fuel 'burnt" is proportional to the heat developed in the reactor. We tend to use electric units in nuclear engineering—in these

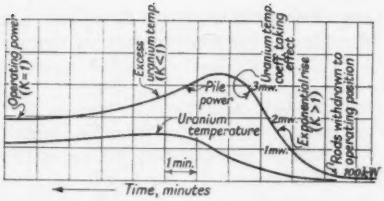

Fig. 2. Typical pile start-up curves

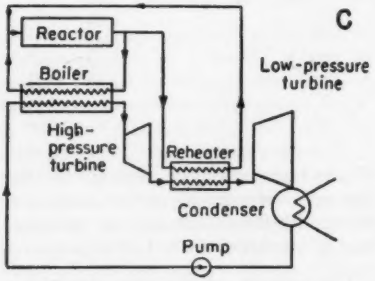

Fig. 3(b) Reheating with reactor coolant after partial expansion is more efficient than using boiler steam; but radiation can seriously complicate piping and shielding, making use of steam preferable

With acknowledgments to "Nucleonics"

units, for each megawatt day of thermal energy developed about one gram of U-235 is destroyed by fission. If you will remember, the balance sheet showed that this will be partially replaced by 0.9 grams of plutonium. This is a valuable secondary fuel since plutonium nuclei are split up by slow neutrons and give out about the same amount of energy as U-235. They have the advantage of giving out three neutrons per fission.

A reactor built as a propulsion unit would have to convey its heat to a steam boiler in the early days of nuclear propulsion, and power might be generated with a thermodynamic efficiency of 20-25 per cent. For each 1000 s.h.p. hr. the unit would therefore consume 4-5 grams of U-235 per day or about 3-4 lb. of fuel per year. This shows in principle the potential attractiveness of nuclear propulsion. Figs. 3(a), (b) and (c) show possible cycles of corresponding efficiencies.

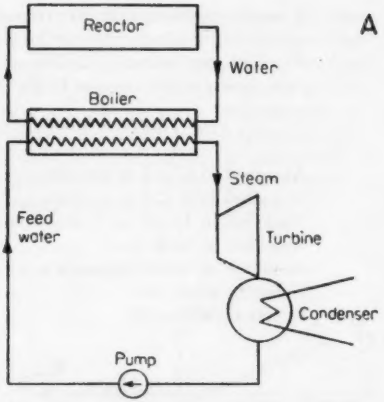

Fig. 3(a) Rankine cycle for deriving power from a water-cooled reactor is used with system shown. Cycle can use saturated or superheated steam. When steam is limited to a temperature less than 500 deg. F., the saturated cycle is more efficient

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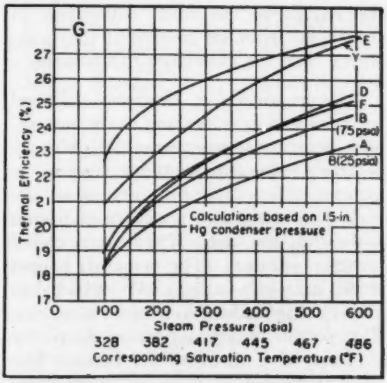


Fig. 3(c) Efficiency curves are lettered to correspond to flow diagrams, with Y for four regenerative stages plus separator, E for 800 deg. F. combustion superheat

With acknowledgments to "Nucleonics"

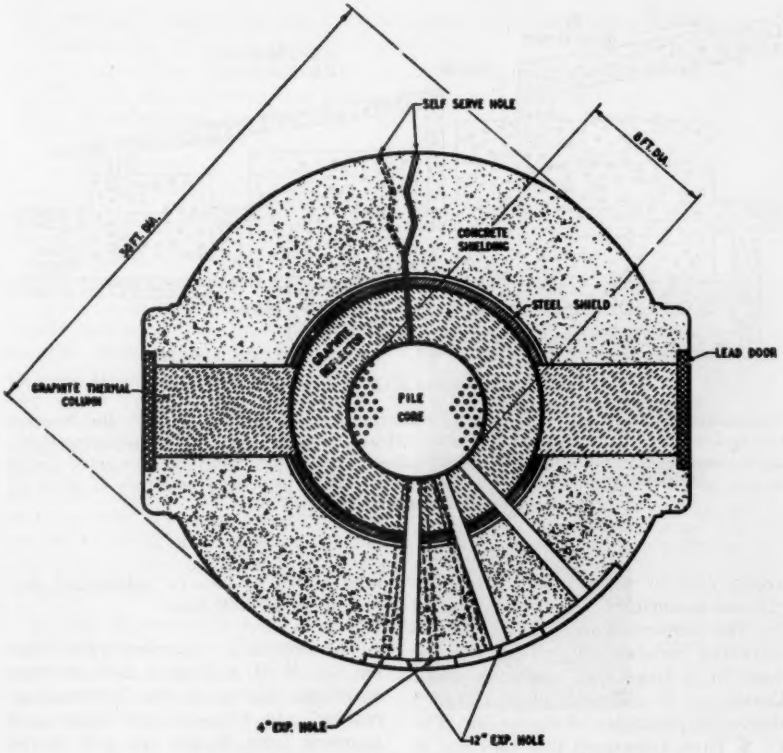


Fig. 4. Plan through working of center line of NRX pile

TYPES OF REACTORS

Reactors for ship propulsion must obviously face limitations of weight. The reacting core has to be surrounded by a shield to prevent the dangerous nuclear radiations from escaping and hurting operating personnel. The shield of the Harwell B.E.P.O. is about 6 feet in thickness and weighs 5000 tons. The core also contains about 800 tons of graphite. Graphite reactors of this type are not, therefore, possible starters for ship propulsion units.

Heavy water reactors are considerably smaller—the reacting core of a low power reactor will be about 6 feet in diameter. But units developing 20,000 kw. of heat will have dimensions rather similar to those of the Canadian reactor which have been published (Fig. 4). The tank diameter is about 10 feet. Surrounding this is a graphite reflector and then there is a concrete shield about 6 feet in thickness. So it is difficult to see how the weight of such a reactor could be reduced below 1000 tons.

For this reason, attention has been focused on reducing the size of the re-

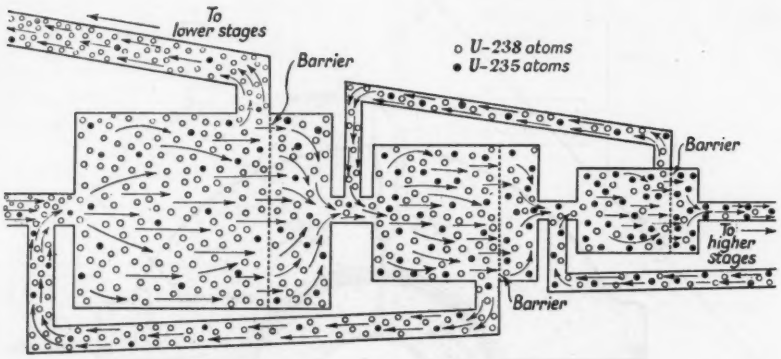


Fig. 5. Process gas flow in K-25 gaseous diffusion process

Schematic diagram. The uranium hexafluoride gas that passes through the barriers becomes enriched in its scarce U-235 atoms (black dots) as it moves through successively higher stages. Gas not passing through barrier, containing mainly the unwanted U-238 atoms (white dots) is returned to lower stages. K-25 plant uses hundreds of acres of barriers, thousands of miles of pipe.

acting core by using a fuel which we refer to as enriched uranium. This fuel has the proportion of U-235 to U-238 increased substantially. This can be done in a large and expensive plant known as a diffusion plant. Fig. 5 shows its principles of operation. The U. S. have announced that they are at the present time building two more plants similar to that at Oak Ridge at a cost of several billion dollars, consuming 3700 megawatts of electric power. They are not therefore likely to be short of U-235.

The U. S. designer has, then, several possible types of reactor to choose from. The USS *Nautilus* will have a "thermal reactor". This means that, just as in the heavy water reactor, the neutrons will be slowed down by a moderator—in this case *ordinary* water—to the low energies where they produce fission easily. The heat is transferred from the fuel elements by water *under pressure* to the steam generator. The overall size and weight of the reactor has not been published but the submarine has been stated to have a submerged displacement of 2500 tons.

The Second U. S. nuclear submarine, the *Sea Wolf*, will use a different type of reactor known as the "intermediate reactor". In this case the high speed neutrons from fission are not slowed down to "thermal energies" but produce their fissions whilst moving at intermediate speeds. This may have a number of advantages. A particular advantage arises from the fact that materials such as stainless steel, which might be used for sheathing fuel elements, absorb *low* energy neutrons strongly, but the absorption is tolerable at intermediate speeds. The absorption of neutrons by the radioactive ash, which is troublesome in operation, will also be substantially reduced. On the other hand, there will be balancing disadvantages—the initial charge of nuclear fuel required may well be greater.

The *Sea Wolf* propulsion system "will transfer the heat from the intermediate reactor by liquid metal in a closed low

TABLE II—SOME OPERATING CHARACTERISTICS OF EXPERIMENTAL BREEDER

Core volume	a regulation football
Na-K alloy temperature at exit	660 deg. F.
Steam pressure at turbine	400 lb. per sq. in.
Generator capacity	250 kw.
Neutron flux	6.5×10^{14} n/in.^{2}/sec.
Power density	4.0 kw./in.^{3}

pressure system to a water steam system to drive a standard steam turbine". Liquid metals are to be used as the heat transfer fluid because of their good thermal transfer properties and their low vapor pressure at high temperatures; they have also a substantial advantage over water in being more stable under irradiation. On the other hand, they introduce technical problems of their own. The exit temperature of the liquid metal will be limited by the corrosion of the metal used for fuel element sheaths.

A first experimental nuclear power unit embodying many of these new principles has operated in the United States for over a year and has been described. This reactor has been built to the design of the Argonne National Laboratory and is installed in the U.S.A.E.C. Reactor Testing Station in Idaho. The reactor is of a type known as a "fast reactor" and goes one step further than the intermediate reactor in that the reactor is designed to slow down the fission neutrons *as little as possible* before producing further fissions. This type of reactor is expected to have advantages over other types in utilizing uranium more efficiently. For the purposes of this paper, its general construction is more interesting. Reactors of this kind must use highly enriched uranium and it has been announced that this reactor has a core "about the size of a regulation football" containing a high proportion of U-235. Fig. 6 shows a drawing of the reactor.

Fig. 6. Experimental breeder reactor
With acknowledgments to "Nucleonics"

The uranium metal will obviously be sheathed in some protective material and the heat is removed by a sodium-potassium alloy, the exit temperature of the liquid metal being 660 deg. F. The liquid metal transfers the heat through a heat exchanger to a secondary heat transfer circuit which takes the heat to a steam generator and power unit where about 250 kw. of power is generated. Fig. 7 shows the general arrangement of this first nuclear power station. This arrangement illustrates one general point in the operation of such units. The liquid metal coolant will become highly radioactive due to the intense

bombardment of neutrons inside the reactor. The external circuit must therefore be heavily shielded. The secondary heat transfer circuit is included to prevent any possibility of radioactivity getting into the power unit proper.

Technical details are given in Table II.

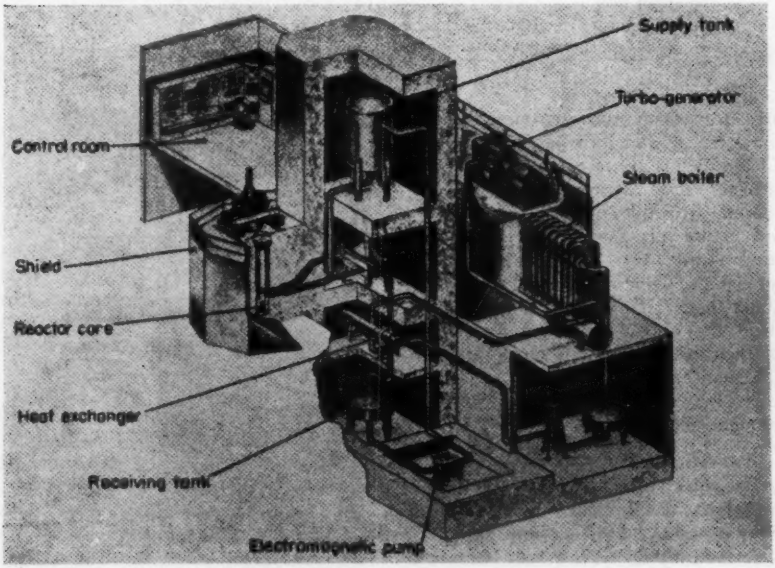


Fig. 7. Experimental breeder reactor and steam-electric generator
With acknowledgments to "Nucleonics"

TECHNICAL PROBLEMS

The technical problems of reactors suitable for propulsion units may be divided into four main classes: physical; metallurgical; chemical and engineering.

The size of the reacting core—the geometrical arrangement of the fuel elements and the shielding required—is a problem for the nuclear physicist, or reactor physicist, as he is coming to be called. One of the difficulties about these advanced reactors is that the calculation of the nuclear performance can only be done very approximately and it is essential, therefore, to build full scale reacting cores operating at zero power —to simplify the experiment—before design can be finalized. This means that the necessary amount of nuclear fuel has to be available and fabricated and this in itself is a costly and time consuming operation. The physicist will also be concerned with problems of conservation of nuclear fuel. The primary fuel, U-235, is very expensive. A U. S. publication quoted at least 20,000 dollars a kilogram. In principle, it is possible to obtain some regeneration of fuel, since surplus neutrons from the reacting

core can be absorbed in U-238 to form plutonium. The physicist will, therefore, look out for possibilities of doing this—neutrons from U-235 must be regarded as extremely valuable and available for reinvestment.

The metallurgist has the difficult problem of producing fuel elements from the difficult metal uranium, sheathing the uranium in a material which is not attacked by the coolant and providing for good thermal contact between uranium and sheath. He has to select materials which are chemically compatible. This problem is made more difficult by the fact that chemical reactions can be enormously speeded up by the intense nuclear radiations inside the reacting core—increases of one thousand-fold are possible. The nuclear radiations also affect the structure of the fuel element. Improvements in metallurgy affect the stability of the fuel elements enormously. The metals used will obviously depend on the type of reactor. A thermal reactor such as the Westinghouse reactor, using high pressure water to transfer the heat, will require a metal which resists corrosion of water at high temperatures—zirconium is an obvious possibility and a large effort is being directed to the development of its metallurgy in the U. S. and some effort in this country. For use in thermal reactors the zirconium has to be separated from the chemically similar hafnium and this in itself is an expensive operation requiring new chemical engineering development, which has been carried out to pilot scale at Harwell. Intermediate reactors may require the development of beryllium metallurgy and will have fuel element problems peculiar to that type of reactor.

The development of fuel elements requires extensive testing in the presence of intense nuclear radiations. This requires the use of testing reactors producing the maximum possible neutron intensity. The Harwell B.E.P.O. and the Canadian pile at Chalk River have been extensively used for such purposes. The Canadian heavy water pile has the great advantage of having at least twenty times the intensity of radiation available in B.E.P.O. so testing times are correspondingly reduced. The Minister of Supply has recently announced that we are to build a new heavy water reactor at Harwell for this purpose.

The radiation chemist has the problem of studying chemical compatibility of reactor materials in the presence of radiation—he also has to use a testing reactor for this purpose. If thermal reactors using water as a moderator or heat transfer medium are being studied he will have the problem of decomposition of the water by the radiation—again requiring testing facilities in reactors. The chemists and chemical engineers have the major problem of processing spent fuel for reactors. The fuel elements may be withdrawn for nuclear reasons—when the U-235 constant has been depleted so much that the reactivity of the core falls to unity. Alternatively, they may be withdrawn for metallurgical reasons—due to deterioration under irradiation or failure of the sheath. In either case they will probably contain a large proportion of the original fuel and may also contain some regenerated fuel—plutonium. They will therefore be valuable and the radioactive ash will have to be extracted and the fuel returned to the metallurgists for processing into new fuel elements. This will require a chemical extraction plant. The design and operation of such plants is complicated by the radioactivity of the radioactive ash (Fig. 8). The costs of such extraction processes must obviously be less than the value of the fuel to be processed. The overall cost of nuclear fuel will largely depend on chemical extraction costs.

The engineer will be concerned with heat transfer problems of liquid media

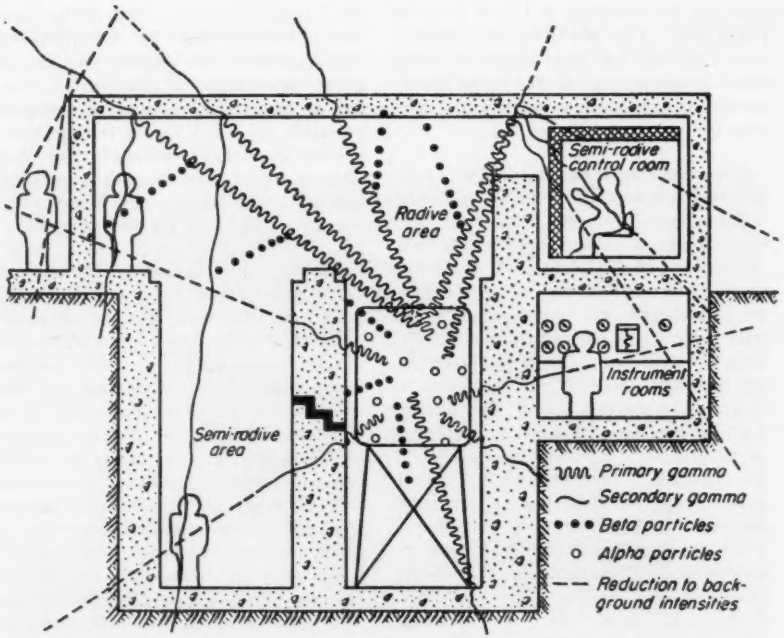


Fig. 8. Distribution of radiation in a radio chemical processing plant
With acknowledgments to "Nucleonics"

and experimental work will have to be done on an extensive scale. He has also the problems of control and safety, bearing in mind the intense radioactivity of the fuel elements, coolant and indeed of all materials in the reactor core. He can never forget the fact that radioactive materials go on developing heat when the reactor is nominally shut down.

You will see that this adds up to a very substantial development program. The U. S. congressional record shows that they are spending about sixty million dollars a year on reactor development.

ECONOMIC PROBLEMS

The cost of nuclear propulsion will contain two main factors—the capital costs and the fuel costs. We have been told that the first experimental nuclear propulsion unit being built in the U. S. will cost about 1400 dollars per kw. equivalent. The total cost of the Westinghouse propulsion unit is stated as twenty-six million dollars, which would correspond to about 20,000 kilowatts equivalent. To translate these into future commercial figures, one might start by taking the "true" dollar-sterling rate as about five and then reducing the cost for subsequent units by a factor of two. This would give a figure of the

order of £140 per kw. as compared with a commercial cost of £50 per kw. for large liners and £40 per kw. for freighters.

Nuclear propulsion unit	£140 per kw.
Large liners	£50 per kw.
Freighters	£40 per kw.

The fuel costs of nuclear propulsion units will depend first on the initial cost of the enriched fuel. A U. S. published figure of "at least 20 dollars a gram" was quoted—so I will double this and take 40 dollars a gram—with a considerable uncertainty factor. It will depend next on the proportion of fuel which can be burnt before reprocessing is necessary and the value to be attached to the spent fuel—this depends on process costs. Both of these factors are at present unknown. However, let us guess that 20 percent of the fuel can be consumed and take no credit for residual fuel. We then arrive at an effective fuel cost of 200 dollars per gram.

Now the heat developed by the consumption of one gram of fuel is 1 megawatt day or 24,000 kw. hours. If we now assume a thermodynamic efficiency of 25 percent, we will develop 6000 kw. hours equivalent at a cost of 200 dollars —say, £60 per gram. This will result in a fuel cost of about 2d. per b.h.p. hour. I must again stress that this figure contains several very uncertain factors. This can be compared with fuel costs for concentrated fuel, based on £7 per ton fuel and 200 steaming days per annum.

Diesel ship m.s. *Bellerophon*	0.38d.[1]
P. and O. cargo liner *Soudan*	0.46d.[2]
Wartime Liberty ships	0.80d.
10,000-ton fast freighter	0.50d.
Large passenger liners	0.50d.
U. S. submarines 8c. per kw. hr.	6d.[3]
"Special projects" 1 dollar per kw. hr. ...	6s.

From these figures it will be seen that on the basis of the guesses made, nuclear fuel costs will be too high to make commercial units practicable in the next decade at least but that they may well compete economically for propulsion of special high cost units such as submarines.

OPERATIONAL FACTORS

The most important operational factor in nuclear propulsion is that it would make possible long voyages between refueling. A propulsion unit developing 10,000 kw. equivalent at an efficiency of 25 percent would consume 40 grams of fuel per day or about 12 kilograms a year. Guessing at a 20 percent fuel utilization before reprocessing, this would require an initial charge of at least 60 kilograms. It would not, therefore, be unreasonable to expect such units to be capable of steaming for a year at full power without refueling. A U. S. official writer has said that this puts the strategic submarine in a role comparable with that of the strategic bomber.

To offset this advantage there is the undoubted disadvantage of operating a propulsion unit which contains a highly radioactive core. The radioactivity from any leakages in operation will certainly make such units more vulnerable.

[1] Arnold, A. G. 1953. Trans. I. Mar. E., Vol. LXV, pp. 57-81.
[2] "Motor Ship", Oct. 1952.
[3] Congressional Record.

FEASIBILITY

It is evident that the development of nuclear propulsion for shipping must depend essentially on the supply of enriched fuel. The U. S. had the great advantage that at the end of the war they had large plants able to produce this material, whereas wartime agreements with the U. S. left Britain with no such plants. With a limited supply of enriched fuel and observing the high priority requirement for its use in other fields, it is difficult to envisage nuclear propulsion units using enriched fuel for more than a few special purpose ships for a long time to come. This situation might change in twenty years if breeding of nuclear fuel had developed by then on a large scale. It has also been considered desirable to concentrate our limited technical and engineering effort on land power stations, as the Ministry of Supply has recently stated. The use of natural uranium reactors using a heavy water moderator is economically more attractive if the heavy weight of the reactor could be accepted. This might, therefore, repay study. In this case, however, the limited supply and high cost of heavy water would be likely to be a major deterrent to this development for some years. The author has no doubt that in due course nuclear propulsion units will operate successfully and that the U. S. will be first in this field. These units will be worth while for special applications such as the submarine. Whether they will extend to wider spheres will depend essentially on the supply and cost of enriched fuel, on how much fuel regeneration is possible and on the development of low cost chemical fuel processing.

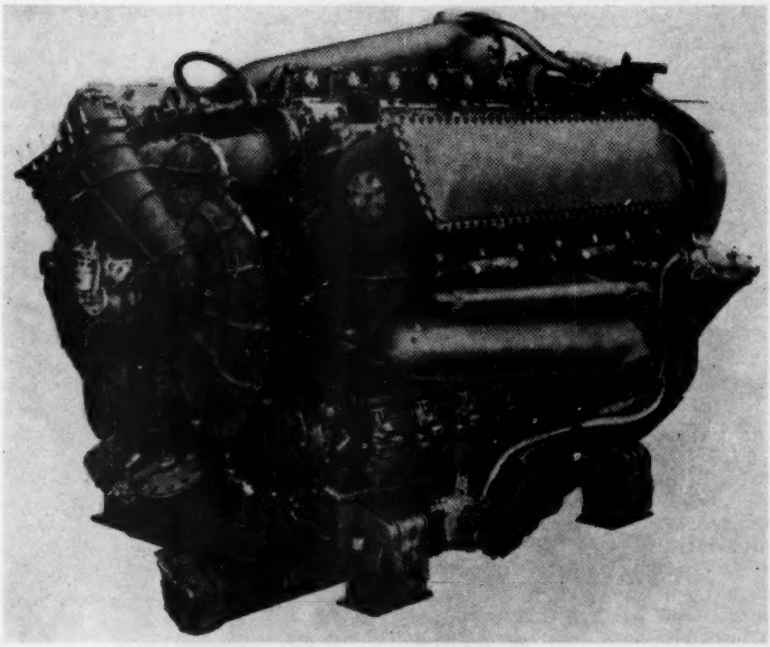


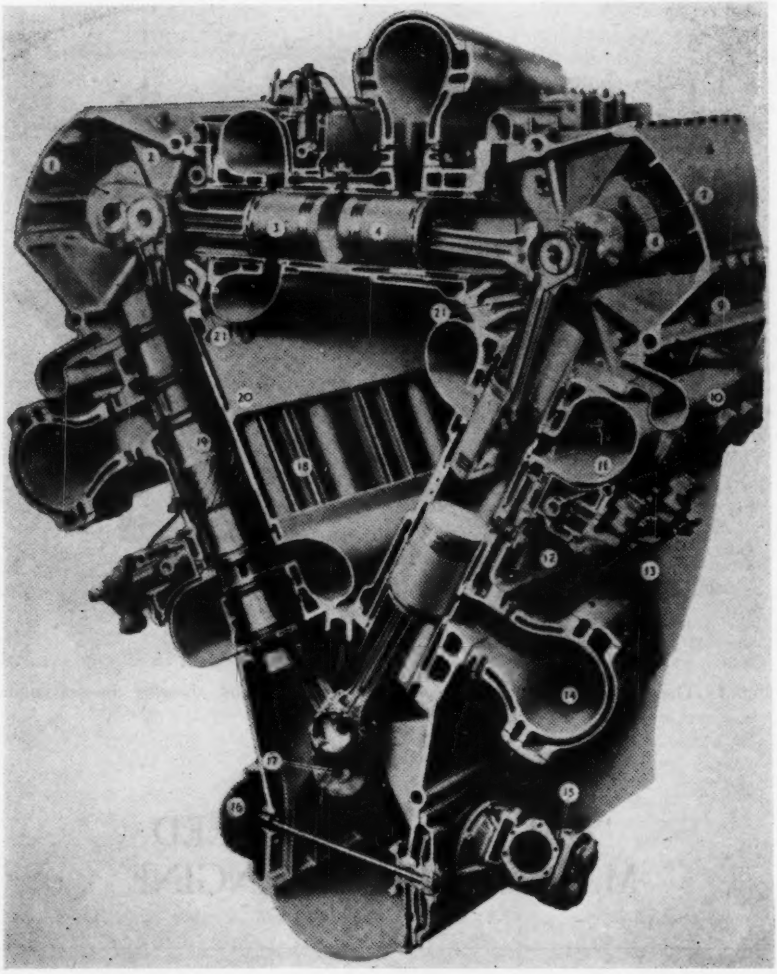
Fig. 1. The Deltic engine viewed from the non-driving end, showing the scavenging blower and resilient mountings

"DELTIC" HIGH-SPEED MARINE DIESEL ENGINE

ACKNOWLEDGMENT

This article was published in the May 1, 1953 issue of "Engineering".

The "Deltic" marine Diesel engine shown in Fig. 1 has been designed and developed for the Royal Navy by D. Napier and Son, Limited. It is an engine of the opposed-piston type, operating on a two-stroke cycle with cylinders arranged in the form of an equilateral triangle, as shown in Fig. 2, to give an extremely compact layout. The bore is 5⅛ in. and the stroke 7¼ in., giving



1 'BC' Crankshaft
2 'BC' Crankcase
3 Inlet Piston
4 Exhaust Piston
5 Crankcase Breather
6 'AB' Crankcase
7 'AB' Crankshaft
8 Main Bearing Cap
9 Crankcase Tie-Bolt
10 Drain Oil Manifold
11 Air Inlet Gallery
12 'A' Camshaft Casing
13 Fuel Injection Pump
14 Exhaust Manifold
15 Sea-Water Pump
16 Fresh-Water Pump and Pressure Oil Pump Drive Gear
17 'CA' Crankshaft
18 Cylinder Block Tie-Bolts
19 Cylinder Liner
20 'C' Cylinder Block
21 Blower Flexible Drive Shafts

Fig. 2. Section through No. 5 row of cylinder, showing tie bolts and blower drive shafts

a total swept volume of 5384 cub. in. and an effective swept volume of 5300 cub. in. The piston speed at 2000 rpm is 2416 ft. per minute; the brake mean effective pressure at maximum power is 91.9 lb. per square inch; and the maximum shaft horsepower, 2500, is reached at 2000 rpm, as shown by the performance curves in Fig. 4. The continuous rating is 1875 s.h.p. at 1700 r.p.m. The engine has 18 cylinders and 36 pistons, which, like all its other components, are small enough to permit the use of modern aero-engine materials and production methods, and all the individual components and major assemblies have been made interchangeable for ease of replacement and maintenance. It is a self-contained power plant, complete with pumps and filters, and control of both the engine and the reverse gear is effected by a single lever. Two of these engines have been installed in the Navy's Fast Patrol Boat 5212, which is an E-boat taken from the Germans at the end of the second World War. They have nearly completed their initial 1000 hours of running at sea. The 5212, based at H.M.S. Hornet, Gosport, recently gave a demonstration run for Press representatives.

The triangular disposition of the cylinders is an unusual departure. With this arrangement, one crankshaft must rotate in the opposite direction from the other two; in this case, it is the bottom one. Two advantages arise from this layout. Firstly, there is automatically a phase-angle difference of 20 deg. between the exhaust and inlet crankshafts, which, with the exhaust crankshaft leading, permits the use of an efficient porting layout for scavenging and cylinder charging. Secondly, each crankpin carries one inlet and one exhaust piston so that the load on each crankpin, and therefore the load transmitted by each crankshaft, is identical. By extending the triangular arrangement through the length of a six-throw crankshaft, with each shaft arranged for a cylinder firing

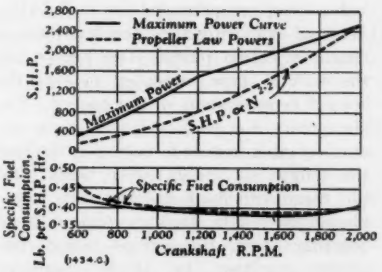


Fig. 4.

order of 1, 5, 3, 4, 2, 6, the resultant 18-cylinder engine has equal firing intervals of 20 deg., giving extremely smooth running.

The triangular body of the engine is built from three identical cast-aluminum six-cylinder blocks which form the sides, and three aluminum crankcases, which form the corners. The upper crankcases are identical, but the lower one is deepened in section to carry engine bearers and to provide for oil drainage. The whole of this unit is held together by high-tensile steel bolts which extend from each crankcase through the cylinder block to the other crankcase. These bolts carry the combustion loads, and the cylinder blocks remain in compression.

The cylinder liners are of the wet type, machined from hollow steel forgings. They are located in the cylinder blocks at one end, and rubber water seals are used. Their bores are chromium-plated and finished by lapping. Exhaust ports are provided around approximately half the circumference at one end and the bars between the ports have holes through them for water cooling. The inlet ports at the other end are arranged around the whole circumference, with a tangential entry angle to impart swirl to the inlet and thereby assist scavenging and mixing. Two injectors, of the outward-opening

valve type, are provided for each cylinder and both injectors are fed from a single injection pump. The pumps are the C.A.V. type, modified to suit the special requirements of the engine. The six pumps for each cylinder bank are carried on a camshaft casing extending the length of the cylinder block, and all three camshaft casings are interchangeable. The rack control is by a rotating shaft, the pumps being connected together by small couplings which are torsionally stiff but axially flexible, thereby eliminating differential expansion effects. The design is so arranged that one pump can be removed and replaced by another and the correct timing and matching be automatically retained.

The special patented pistons, shown in Fig. 3, are constructed of two parts held together by a spring circlip. The inner member is machined from a Y-alloy forging and carries a hardened-steel gudgeon pin which fits tightly in it. The outer member is cast aluminum. It has an unbroken skirt and is provided with a cast-in austenitic-iron insert, in which the two top gas rings are seated. Between the outer and inner members is an annular chamber for cooling purposes; it extends from the bottom of the skirt to behind the gas rings. Grooves in the side connect with others that run across the top of the inner member and pass directly beneath the piston crown. Oil is fed to this chamber from the connecting rod, and escape holes are provided. It is claimed that the movement of the piston and continuous flow of the oil cause swilling around these surfaces and aid cooling. The connecting rods are made from high-tensile steel stampings, machined and polished all over, and the two rods connecting to one crankpin are in the form of a fork and blade, one big-end fitting between the yoke of the other. The big-end of the forked rod is fitted with a steel shell, nitrided on its outer surface and carrying in its bore a steel-strip bearing, lead-bronze lined and lead-plated, which runs direct on the crankpin. The outside surface of the shell provides the bearing surface for the blade rod, the big end of which is also fitted with a steel-strip lead-bronze and lead-coated bearing. The small ends of both rods are drilled for the purpose of feeding oil from the crankpin for small-end lubrication and for piston cooling. The seven-bearing crankshafts are nitrided all over, and the bearing surfaces finished by lapping. The main journals run in steel-strip lead-bronze and lead-plated bearings carried direct in the cast-aluminum crankcases. Oil is supplied to each journal through oil galleries extending the length of the crankcase and thence through passages in the crankshafts to the crankpins.

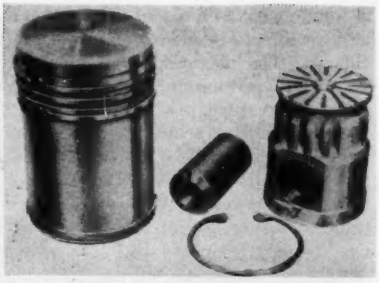


Fig. 3. Piston Components

The three crankshafts are coupled together through gears at one end, and drive a common output shaft, at the center of the triangle, which runs slightly faster than the crankshafts. By alternative assemblies of idler gears in this phasing system the output shaft rotation can be reversed, the crankshaft rotation remaining unchanged, thus providing a method of meeting the requirement for engines having "handed rotation." The reverse and reduction gearing takes the form of two constant-mesh systems, one for ahead running and one for astern, the appropriate gear train being connected when required by hydraulically-loaded plate clutches. The clutches con-

nect to the output shaft from the phase gear train, and the clutch controls are interconnected with the engine power control. The gear trains in the reverse gearbox also provide appropriate speed reductions; the crankshaft to propeller-shaft gear ratio is 2.106 ahead and 2.397 astern. All main drives for camshafts, pumps, scavenge blower, and other auxiliaries are taken from the driving end of the engine.

Scavenge air for the engine is supplied by a single-stage double-side centrifugal blower. The impeller is cut from a Y-alloy forging and it delivers air through a diffuser into a casing having three exits, one to each bank of cylinders. The blower is driven by two flexible shafts connecting with gears at the driving end of the two top crankshafts. The lubrication system is the dry-sump type, and all bearings and gear meshes are supplied with oil under pressure; the oil is returned to the tank by a scavenge pump. A heat exchanger cooled by seawater is used for cooling the oil, and thermostats control the oil temperature. The engine is water-cooled and the cylinder jackets form part of a closed system in which distilled water is circulated through a heat exchanger by a centrifugal pump. A thermostatic control is fitted in the circuit and the heat exchanger is cooled by sea-water circulated by a gear-type pump. The starting of the engine is performed by a combustion-type starter, cartridge-operated, the claw of which engages a gear meshing directly with one of the upper crankshafts. The overall length of the engine, including reverse gear, is 10 ft. 11 in., the width is 6 ft. 2½ in., and the height is 7 ft. 1 in. The dry weight, including the reverse gear, is 10,500 lb.

THE EFFECT OF RADIAL-PITCH VARIATION ON THE PERFORMANCE OF A MARINE PROPELLER

ACKNOWLEDGMENT

This article is an abstract of a paper presented to the Institution of Naval Architects in March, 1953, by PROFESSOR L. C. BURRILL and C. S. YOUNG. It was published in the June, 1953 issue of "The Shipbuilder and Marine Engine-Builder".

INTRODUCTION

In this investigation, strip-theory calculations were first of all made for an actual four-blade aerofoil propeller of good modern design, as fitted to a large twin-screw liner, and the results were found to be closely in agreement with expectations, and with the tank-test figures. Details of this propeller are given in Fig. 1. Various alternative pitch-lines were then drawn out, representative of possible practical alternatives, and complete calculations were made for a series of screws having the same blade-shape, sections, etc., as the

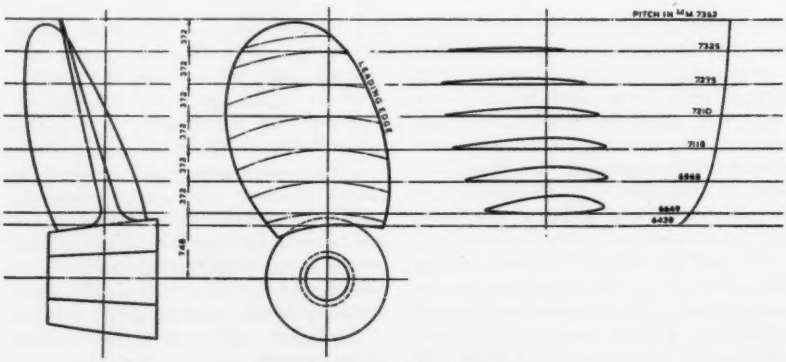


Fig. 1.—Drawing of Basic Propeller.

Diameter, 5,980 mm.; mean pitch, 7,200 mm.; surface, 14·27 m.²; B.A.R., 0·514; blades, four right-hand and four left-hand; N = 95 r.p.m.; Va = 16·50 knots; corresponding J = 0·90, K_Q = 0·0372.

basic propeller, and differing only in respect of the shape of the pitch-variation line from root to tip.

For simplicity, these calculations were first made for all the propellers working in a uniform stream, corresponding to the mean wake-speed of the original design, and later the investigation was extended to cover various non-uniform streams, representative of a twin-screw wake of 0.16 and of single-screw wakes of 0.225, 0.30 and 0.34, respectively (Taylor nomenclature).

In addition to the various arbitrary pitch-lines mentioned, further calculations were later made with pitch-curves corresponding to the methods proposed by several investigators for the design of propellers with minimum energy loss, both for the uniform stream and for the variable wake streams listed above.

The method of calculation used throughout the investigation enables the performance characteristics for arbitrarily defined propellers to be calculated on a consistent basis and allows the variations in lift and drag, in terms of angle of incidence, to be calculated in a predetermined manner consistent with reliable wind-tunnel data, thus putting the alternative performance figures on a strictly comparative basis.

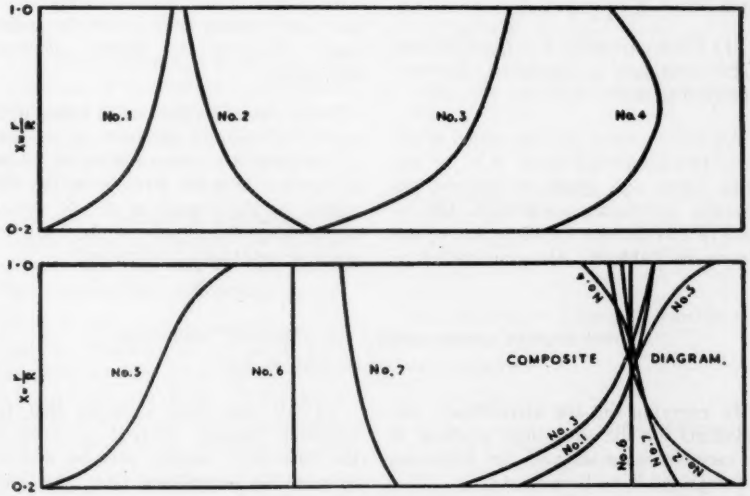


Fig. 2.—Sketch showing Arbitary Pitch Variations Examined (Pitch Lines 1—7).

PROPELLERS WORKING IN A UNIFORM STREAM

A description of the several pitch-variations examined is as follows (see Fig. 2).—

(1) Pitch curve No. 1.—As for original, or basis propeller, with hyperbolic pitch-reduction line. Reduction at root 14 percent.

(2) Pitch curve No. 2.—Pitch increase from tip to root, with radial distribution image of original line. Increase at root 13 percent.

(3) Pitch curve No. 3.—Pitch decrease from tip to root, with similar curve to No. 1, but reduction about 1½

times as great. Reduction at root 18 percent.

(4) Pitch curve No. 4.—Similar reduction at root as for No. 1, but with outer pitches reducing rapidly towards tip from $r/R = 0.65$. Reduction at root 10½ percent, reduction at tip 4½ percent, maximum at $x = 0.65$.

(5) Pitch curve No. 5.—Similar reduction at root as for No. 1, but with outer pitches increased rapidly towards tip from $r/R = 0.65$. Reduction at root 12 percent, increase at tip 6½ percent, inflection at $x = 0.65$.

(6) Pitch curve No. 6.—Constant-pitch line.

(7) Pitch curve No. 7.—Derived from Betz's contstant η_1 condition. Increase at root 5 percent.

All these screws were designed to absorb the same delivered H.P. at the same r.p.m. and speed of advance, the diameter remaining unchanged. The results of calculations for these screws are shown in Table I. An examination of the final column shows that the calculated efficiency is almost identical throughout.

TABLE I

Propeller with pitch reduction curve	k_Q	Deviation of K_Q from 0·03716	k_T	η
		%		
No. 1	0·03716	0	0·18795	0·725
No. 2 .. .	0·03696	−0·54	0·18693	0·725
No. 3	0·03710	−0·16	0·18798	0·726
No. 4	0·03722	+0·16	0·18825	0·725
No. 5 . ..	0·03734	+0·42	0·18853	0·724
No. 6	0·03703	−0·30	0·18731	0·725
Derived from Betz condition	0·03743	+0·73	0·18947	0·725

K_Q, K_T, AND η FOR VARIOUS ARBITRARY PITCH LINES IN UNIFORM STREAM

From these calculations, it seems difficult to increase the efficiency at one part of the propeller without bringing about a decrease at some other part, the efficiency in the region of 0.7 R, which carries the major part of the load, remaining substantially constant.

STRIP-THEORY CALCULATIONS FOR A MARINE PROPELLER WORKING IN A VARIABLE WAKE

In carrying out the strip-theory calculations for the propellers working in a variable wake-stream, the following assumptions have been made.

(1) The radial variation of wake corresponding to each mean wake factor has been determined by applying the data published by Professor W. P. van Lammeren (for both the single- and twin-screw wakes).

(2) No account has been taken of circumferential variations in wake.

(3) It has been assumed that each blade element may be treated independently.

(4) It has been assumed that the Goldstein factors, derived in terms of the local flow angles, may be applied, despite the departures from the ideal flow condition.

It soon became evident that, starting from a fixed nominal mean wake and finding the corresponding radial distribution of speed, the total K_T and K_Q for a given propeller were smaller than those obtained for the uniform stream. That is to say, the speed of advance Va, in open water, required to be increased slightly in order to obtain the same total K_T, and still further to obtain the same total K_Q.

It is important to note that as the same wake-pattern leads to different mean wake values, on the basis of volumetric mean, thrust-equivalent mean, or torque-equivalent mean, respectively, this result is reflected in the assessment of the total efficiency of the whole propeller when working in a variable wake. In order to clarify this position, the new symbols η_N, η_T and η_Q have been introduced, and the alternative methods of assessing the efficiency in the variable wake condition have been classified as follows:—

(i.) Nominal Efficiency.—If the mean speed of advance of the propeller is calculated by using the nominal wake, η_N may be referred to as the *nominal efficiency.*

(ii.) Thrust-identity Efficiency.—If the mean speed of advance is calculated by applying the principle of thrust equality *(i.e.,* original Froude method), then the efficiency η_T may be referred to as the *thrust-identity efficiency.*

(iii.) Torque-identity Efficiency.—If the mean speed of advance for torque-identity is used, η_Q may be referred to as the *torque-identity efficiency.*

There is still another method of assessing the efficiency of the whole propeller when working in a variable wake, which may be considered. If the blade element at x is considered to be advancing with speed Va' relative to the medium, and producing the elementary thrust $d\,T/dx$, then the integrated useful work done by the propeller in non-dimensional form may be expressed as

$$U_V = \int_{x=b}^{1\cdot0} J' \left(\frac{d\,k_T}{d\,x}\right) d\,x$$

where $J' = Va'/N\,D$, which varies with x, and is hence a function of x.

$$\text{Now,}\quad K'_T = \frac{d\,T/d\,x}{\rho\,N^2\,D^4} = \frac{d\,(K_T)}{d\,x}$$

and the mean speed of advance coefficient will become

$$J_V = \frac{\int J' \left(\frac{d\,K_T}{d\,x}\right) d\,x}{K_T}$$

so that the corresponding efficiency becomes

$$\eta_V = \frac{J_V}{2\,\pi} \times \frac{K_T}{K_Q} = \frac{\int_{x=b}^{1\cdot0} (J'\,K'_T)\,d\,x}{2\,\pi} \times \frac{1}{K_Q} = \frac{1}{2\,\pi} \times \frac{U_V}{K_Q}.$$

This efficiency will here be referred to as the *virtual efficiency,*

i.e.,

$$\eta_V = \frac{\int (J'K'_T)\,d\,x}{2\,\pi\,.\,K_Q} = \textit{virtual efficiency.}$$

CALCULATIONS FOR ORIGINAL PROPELLER WORKING IN DIFFERENT VARIABLE-WAKE STREAMS

In order to exemplify the foregoing remarks, Table II. and Fig. 3 have been prepared, showing the results obtained from calculations for the original propeller working in variable wake-streams corresponding to a twin-screw wake of $W_N = 0.16$ and single-screw wakes of $W_N = 0.225$, 0.30 and 0.34, respectively.

TABLE II.

Items	Open water condition	Wake condition				Remarks
		Twin screw	Single screw			
C_{pv}	—	0·84	0·78	0·86	0·88	
W_N	Nil	0·16	0·225	0·30	0·34	
J or J_N	0·90	0·90	0·90	0·90	0·90	
K_Q	0·03716	0·03682	0·03565	0·3444	0·03390	
K_T	0·18795	0·18621	0·18318	0·17975	0·17794	
Difference of K_Q from 0·03716	—	−0·92%	−4·04%	−7·32%	−8·62%	
Difference of K_T from 0·18795	—	−0·93%	−2·54%	−4·36%	−5·32%.	
J or J_N	0·9	0·90	0·90	0·90	0·90	
J_Q	—	0·906	0·9255	0·945	0·954	V/n D
J_T	—	0·905	0·913	0·922	0·9265	
J_V	—	0·907	0·887	0·865	0·838	
W_N	—	0·160	0·225	0·300	0·340	
W_Q	—	0·154	0·204	0·265	0·301	$\frac{V_s - V_a}{V_s}$
W_T	—	0·155	0·214	0·283	0·321	
W_V	—	0·153	0·235	0·334	0·386	
η or η_N	0·725	0·725	0·737	0·748	0·752	
η_Q	0·725	0·729	0·757	0·785	0·797	Behind efficiencies
η_T	0·725	0·728	0·747	0·766	0·775	
η_V	0·725	0·730	0·727	0·711	0·700	
η open at J corresponding to J_N	—	0·725	0·725	0·725	0·725	
η open at J corresponding to J_Q	—	0·7275	0·736	0·744	0·749	Open efficiencies
η open at J corresponding to J_T	—	0·727	0·731	0·735	0·737	
η open at J corresponding to J_V	—	0·728	0·718	0·703	0·693	
$R.R.E_N$	—	1·00	1·017	1·032	0·037	
$R.R.E_Q$	—	1·002	1·029	1·056	1·065	
$R.R.E_T$	—	1·001	1·022	1·043	1·050	
$R.R.E_V$	—	1·003	1·011	1·011	1·010	

CALCULATED RESULTS FOR BASIC PROPELLER IN SEVERAL VARIABLE WAKE STREAMS

TABLE III.

Propellers having pitch reduction curve No.	K_Q	Deviation of K_Q from 0·03716	K_T	η_N	J_V	η_a	W_N
		%					
1	0·03716	0	0·18809	0·725	0·907	0·731	
2	0·03716	−0·03	0·18819	0·725	0·906	0·731	
3	0·03725	+0·24	0·18764	0·722	0·948	0·728	0·16
4	0·03695	−0·57	0·18665	0·724	0·908	0·730	
5	0·03707	−0·24	0·18788	0·726	0·908	0·730	
1	0·03728	+0·32	0·19096	0·734	0·883	0·725	
2	0·03705	−0·30	0·18988	0·734	0·871	0·710	
3	0·03751	+0·89	0·19202	0·733	0·881	0·718	0·225
4	0·03691	−0·67	0·18914	0·735	0·877	0·716	
5	0·03702	−0·38	0·16711	0·735	0·879	0·716	
1	0·03733	+0·46	0·19375	0·743	0·850	0·703	
2	0·03685	−0·84	0·19169	0·745	0·8235	0·683	
3	0·03748	−0·86	0·19473	0·744	0·855	0·707	0·30
4	0·03716	0	0·19277	0·743	0·846	0·699	
5	0·03695	−0·56	0·19245	0·745	0·856	0·710	
1	0·03707	−0·24	0·19391	0·749	0·832	0·692	
2(*a*)	0·03718	+0·05	0·19378	0·746	0·823	0·682	0·34
2(*b*)	0·03696	−0·81	0·19194	0·744	0·826	0·682	
3	0·03709	−0·19	0·19341	0·747	0·841	0·698	

K_Q, K_T, and EFFICIENCIES, FOR VARIOUS ARBITRARY PITCH LINES IN SEVERAL VARIABLE WAKE STREAMS. W_N = 0·16, 0·225, 0·30 AND 0·34

(*a*) Calculated by assuming linear relationship between C_L AND α.
(*b*) Calculated by assuming non-linear relationship between C_L and α, based on experimental data from N.A.C.A. reports.

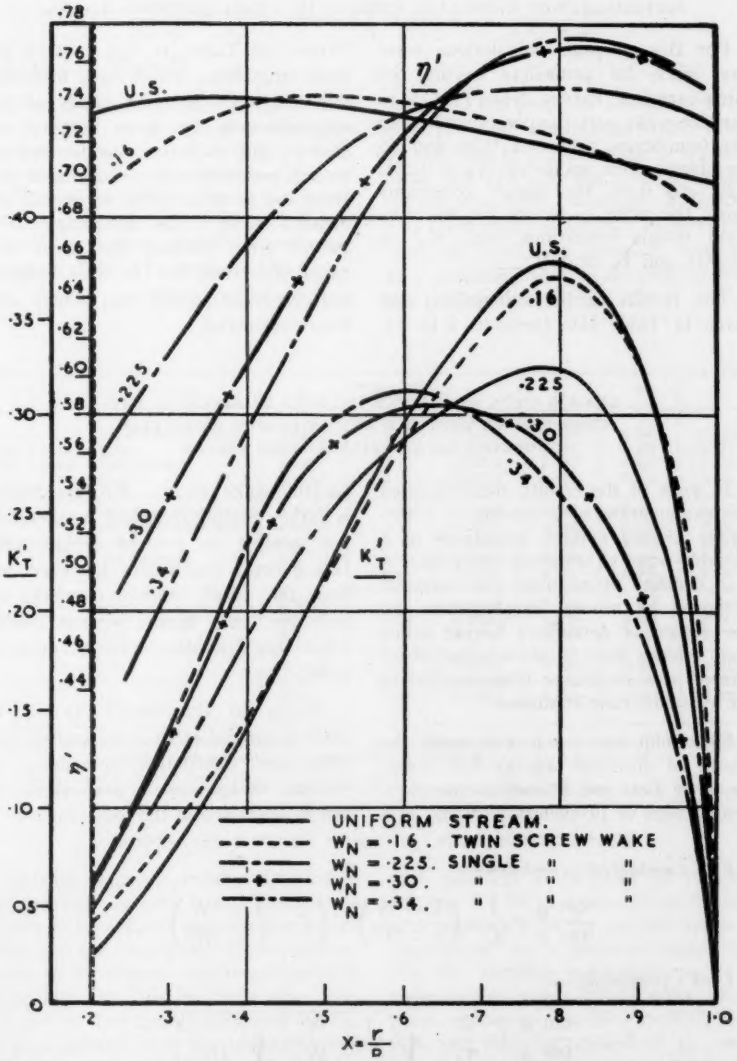


Fig. 3.—K_T and Efficiency Curves for Basic Propeller in Several Variable-wake Streams.

EXAMINATION OF THE EFFECT OF RADIAL-PITCH VARIATION ON THE PERFORMANCE OF PROPELLERS WORKING IN A VARIABLE-WAKE STREAM

For this purpose, calculations were first made for propellers having the pitch-variation curves Nos. 1 to 5 in variable-wake patterns corresponding to the twin-screw wake of 0.16 and to the single-screw wakes of $W_N = 0.225$, 0.30 and 0.34, the design conditions being the same as before for the uniform stream conditions, *viz.*, $K_Q = 0.03716$ and $J_N = 0.90$.

The results of the calculations are given in Table III. (sections 1 to 4). From this Table, it will be seen that these propellers, which have materially different pitch-variation curves, all give approximately the same nominal efficiency; and, as before, for the uniform stream conditions, it is concluded that, from the point of view of overall efficiency; there is no advantage to be gained from varying the pitch in a radial direction, for the wide range of variable-wake conditions which have been considered.

EXAMINATION OF VARIOUS METHODS OF APPLYING THE CONDITION OF MINIMUM ENERGY LOSS TO PROPELLERS WORKING IN A VARIABLE-WAKE STREAM

In view of the results obtained from the examination of a number of alternative arbitrary pitch variations in a variable-wake of different intensities, it was decided to examine the methods proposed by several investigators for the design of propellers having minimum energy loss, to see whether these offered any advantage when applied to the variable-wake condition.

Helmboldt was the first to apply the theory of minimum energy loss introduced by Betz and Prandtl to the practical design of propellers working in a variable-wake stream, but his method is rather complicated, and is, therefore, not suitable for routine design work. His general conclusion, however, was that the ideal minimum energy-loss principle leads to the highest loading where the frictional wake is most intense.

Owing to the complexity of his method, several other investigators have introduced alternative procedures for routine design work, and these are briefly described in the following:—

Van Lammeren's condition.—

$$\frac{\tan \phi}{\tan \psi} = \frac{1}{\eta_i} \cdot \left(\frac{1 - W}{1 - W'}\right) + \left(1 - \frac{1 - W}{1 - W'}\right).$$

Lerb's condition.—

$$\frac{\tan \phi}{\tan \psi} = \frac{1}{\eta_i} \cdot \sqrt{\frac{1 - W}{1 - W'}} \cdot \sqrt{\frac{1 - t'}{1 - t}}.$$

Van Manen and Balhan's condition.—

$$\frac{\tan \phi}{\tan \psi} = \frac{1}{\eta_i} \cdot \left(\frac{1 - W}{1 - W'}\right) \cdot \left(\frac{1 - t'}{1 - t}\right).$$

RADIAL-PITCH VARIATION

Betz's condition.—

$$\frac{\tan \phi}{\tan \psi} = \frac{1}{\eta_i} = \text{constant} \left(\text{where } \eta_i = \frac{1 - a'}{1 + a} \right).$$

and $\tan \psi = V'_a / n D$.

These conditions have been applied to the design of propellers working in the twin-screw wake of $W_N = 0.16$, and the single-screw wakes $W_N = 0.225$, 0.30 and 0.34, the basic design conditions being $J_N = 0.90$ and $K_Q = 0.03716$, as before, and the results are shown in Table IV., sections 1 to 4.

As the various alternative methods of designing the propeller according to the ideal principle of minimum energy loss do not lead to higher value of η_N than those obtained with the arbitrary pitch-curves previously examined, it appears that there is no advantage to be gained from designing the propeller, working in a variable wake, in accordance with any of these conditions.

TABLE IV.

W_N	Condition	K_Q	Deviation of K_Q from 0·03716	K_T	η_R	J_T	η_T
			%				
$W_N = 0.16$ ($W_F = 0.19$)	Van Manen and Balhan	0·03714	−0·50	0·18767	0·724	0·900	0·724
	Lerbs	0·03734	+0·50	0·18809	0·722	0·908	0·728
	Van Lammeren ..	0·03711	−0·13	0·18743	0·723	0·905	0·728
	Betz	0·03725	+0·24	0·18795	0·723	0·910	0·731
$W_N = 0.225$	Van Manen and Balhan (*a*)	0·03728	−0·32	0·18758	0·721	0·851	0·682
	Van Manen and Balhan (*b*)	0·03625	−2·45	0·18166	0·717	0·863	0·688
	Lerbs	0·03720	+0·11	0·19150	0·737	0·878	0·719
	Van Lammeren ..	0·03732	−0·16	0·19014	0·732	0·895	0·728
	Betz	0·03731	+0·40	0·18792	0·721	0·909	0·726
$W_N = 0.30$	Lerbs	0·03710	−0·16	0·19234	0·743	0·862	0·711
	Van Lammeren ..	0·03709	−0·19	0·18901	0·733	0·892	0·726
	Betz	0·03707	−0·24	0·18325	0·708	0·929	0·730
$W_N = 0.34$	Lerbs	0·03710	−0·08	0·19321	0·746	0·851	0·705
	Van Lammeren ..	0·03733	+0·19	0·18990	0·730	0·895	0·727
	Betz	0·03715	−0·03	0·18218	0·702	0·936	0·730

K_Q, K_T, AND EFFICIENCIES, FOR PROPELLERS DESIGNED FOR VARIOUS MINIMUM ENERGY LOSS CONDITIONS, IN SINGLE-SCREW WAKE STREAM $W_N = 0.16$, AND TWIN-SCREW WAKE STREAMS $W_N = 0.225$, 0·30 AND 0·34

(*a*) Calculated by assuming linear relationship between C_L AND α.
(*b*) Calculated by assuming non-linear relationship between C_L and α, based on experimental data from N.A.C.A. reports.

DIFFERENCE BETWEEN NOMINAL AND EFFECTIVE WAKES

Arising from the results obtained in the previous sections, it was thought desirable to investigate the effects of pitch-ratio and the magnitude of the nominal wake on the thrust- and torque-identity wake factors. This has been done with the aid of data kindly provided by Dr. J. F. Leathard from the extensive calculations which he made for the B.4.55-type screw.

With these data, calculations have been made for propellers having the same sections as the B.4.55 screw, but with uniform pitch-ratios of 0.6, 0.8, 1.0 and 1.2 for a moderate range of J (corresponding to the normal range of application) for a uniform stream, and also for variable-wake streams corresponding to single-screw wake variations appropriate to $W_N = 0.15$, 0.20, 0.30 and 0.35, for values of J_N corresponding to the optimum conditions for each pitch-ratio. The results, which are consistent with those previously obtained, have been plotted in Figs. 4 and 5.

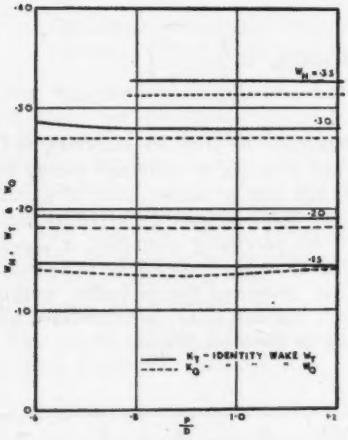


Fig. 4.—Effect of Pitch-ratio on Relationship between W_T, W_Q and W_N.

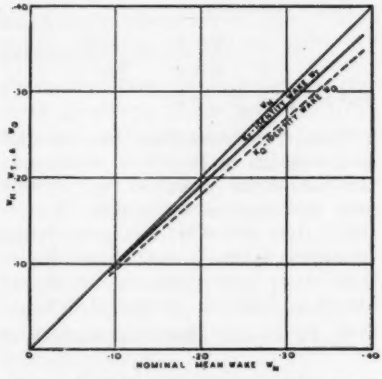


Fig. 5.—Relationship between W_T, W_Q, and W_N to Base of Nominal Mean Wake Factor W_N.

As a result of these calculations, it is concluded that the difference between the nominal and effective mean wakes is nearly the same for propellers from $P/D = 0.6$ to 1.2 and the results shown in Fig. 5 can, therefore, be used for determining the corresponding values of W_N for calculation purposes, when the values of W_T or W_Q are known from previous data.

GENERAL CONCLUSIONS

The results obtained from the foregoing calculations suggest the following conclusions:—

(1) From the point of view of overall efficiency, and apart from any consideration of cavitation or flow break-down, there appears to be no material advantage to be gained from the adoption of a radial variation of pitch, both in a uniform stream and in a variable-wake stream.

(2) In particular, it seems that there is no special advantage to be gained from the application of the various alternative methods of design, based on the principle of minimum energy loss.

(3) On the other hand, no special loss in efficiency is to be expected from the adoption of moderate pitch-variations which are favorable from the point of view of cavitation or flow break-down, and this leaves the designer considerable freedom in the matter of adopting such alternative pitch-variation lines from root to tip of the blades as might be considered desirable from this point of view.

(4) It appears that the quantity designated relative-rotative-efficiency has a real meaning, in terms of the methods of analysis usually adopted, and its value can be estimated by calculation.

(5) The nominal wake factor is slightly larger than the corresponding thrust-identity wake factor, and this in turn is somewhat greater than the equivalent torque-identity wake factor.

(6) The value of the nominal behind-efficiency η_N, for a propeller working in a variable-wake stream, appears to increase slightly as the value of W_N is increased for the same value of J_N or nominal mean wake speed V_a.

A STABLE NUMERICAL SOLUTION FOR TRANSIENT HEAT FLOW[1]

GEORGE LEPPERT

THE AUTHOR

served in the United States Navy from 1943 to 1946, is a qualified submarine officer and member of the ASNE. He received the B.S. Degree in Mechanical Engineering from the University of Wisconsin in 1947 and the M.S. Degree from Illinois Institute of Technology in 1952.

As a member of the Reactor Engineering Division of Argonne National Laboratory, he was engaged in the design of a nuclear power plant for submarine propulsion. He recently joined the General Engineering Department of Monsanto Chemical Company as Manager, Engineering Research Section.

An implicit finite difference formula for the numerical integration of the heat conduction equation is described. It is shown to offer considerable saving in computing time compared to previously used methods for some types of problems. A simple algebraic procedure is developed which facilitates the computation on a desk-type calculating machine and removes the necessity for either iteration or tedious successive substitution at each time step. The accuracy of the method is discussed in terms of its convergence and stability with the aid of a simple example whose analytical solution is known. Although the outstanding advantage of the new method is its stability for large time steps, its convergence error also tends to be smaller than for the explicit formula usually used in these problems.

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[1] Acknowledgment: This paper was presented at the Semi-Annual Meeting of the American Society of Mechanical Engineers in October, 1953.

NOMENCLATURE

The following nomenclature is used in the paper:

a, b, C = constant numerical coefficients, used with subscripts for identification

c = heat capacity of unit mass of substance

i, j, k = integers (subscripts)

k = thermal conductivity

$M = (\triangle x)^2/\alpha \triangle t$ (dimensionless)

m = integer (subscript) locating a point along the x-axis, i.e., $m = x/\triangle x$

n = integer (subscript) locating a point on the time axis, i.e., $n = t/\triangle t$

t = time measured from beginning of problem

x = distance from plane of symmetry to a point in the body measured in direction of heat flow

y, z = distances perpendicular to direction of heat flow, measured from x-axis

$\triangle t$ = finite time interval

$\triangle x, \triangle y, \triangle z$ = finite space intervals in the x, y and z directions, respectively

$\alpha = k/\rho c$, thermal diffusivity

θ = temperature excess over a reference temperature

θ^* = temperature excess found by finite difference solution for $\triangle x = 0.2$ ft.

θ_{ma} = temperature excess found by analytical solution

$\theta_{m,\, n+\frac{1}{2}} = \dfrac{\theta_{m,\, n+1} + \theta_{m,\, n}}{2}$, arithmetic average of temperature excess over a time interval $\triangle t$.

ρ = density

INTRODUCTION

The object of this paper is to describe a recently developed numerical method for the solution of partial differential equations of the heat conduction type and to show how this procedure may be applied simply to certain types of engineering problems. For comparison, however, the well-known numerical method which has been applied by Emmons (1),[2] Dusinberre (2) and others, will also be discussed.

[2] Numbers in parentheses refer to similarly numbered references in bibliography at end of paper.

The present purpose will be served by writing the partial differential equation of heat flow in the simple form

$$\frac{\partial \theta}{\partial t} = \alpha \frac{\partial^2 \theta}{\partial x^2} \qquad [1]$$

together with the corresponding difference equation

$$\frac{\theta_{m,\,n+1} - \theta_{m,\,n}}{\triangle t} = \frac{\theta_{m+1,\,n} - 2\theta_{m,\,n} + \theta_{m-1,\,n}}{(\triangle x)^2} \qquad [2]$$

Equation [2] may be solved for the future temperature $\theta_{m,\,n+1}$ at any point $m\triangle x$ at a time $\triangle t$ later than the time at which the temperature distribution is known.

$$\theta_{m,\,n+1} = \frac{\theta_{m+1,\,n} + (M\text{-}2)\theta_{m,\,n} + \theta_{m-1,\,n}}{M} \qquad [3]$$

Because the finite difference substitution [2] yields for the unknown temperature at each point an explicit algebraic equation, it will be referred to in the present paper as the *explicit substitution.*

DISCUSSION

In a comprehensive mathematical study of the subject, O'Brien, Hyman and Kaplan (3) have shown that the accuracy of a finite difference solution may be discussed conveniently in terms of the "convergence" and "stability" of the difference substitution employed. The discrepancy between the exact solution of the partial differential equation (e.g., equation [1], above) and the exact solution of the corresponding difference equation (e.g., equation [2], above) is called "truncation error" and is related to the convergence. The discrepancy between the exact solution of the difference equation and the actual numerical solution of the same equation is called the "numerical error" or "round-off error" and is related to the stability.

The truncation error, produced by the finite space and time divisions in the difference equation, may be thought of as the error introduced by the replacement of an infinite series solution to a partial differential equation by a finite series ("truncated" series) whose sum is the exact solution to the difference equation. Although experience will usually guide the selection of a suitable mesh size in space and the stability limitation (where it exists) will fix the maximum time interval once the space interval is chosen, the obvious test for convergence error where doubt exists is to repeat the calculation with a finer mesh and compare the two solutions. This idea is illustrated in a subsequent example.

Various writers have considered the stability of the explicit difference substitution, with the well-known conclusion that the solution is unstable unless $M \geq 2$. It sometimes happens that this stability restriction prevents the use of the method because the size of time step, $\triangle t$, becomes so small compared with the total time for which the solution is desired that an excessive number of steps are required in the computation. This difficulty may frequently be avoided, however, by the use of a different procedure which is described on the following page.

Consider the following pairs of difference representations of the temperature gradient:

$$\frac{\theta_{m+1,\,n} - \theta_{m,\,n}}{\triangle x} \quad ; \quad \frac{\theta_{m,\,n} - \theta_{m-1,\,n}}{\triangle x} \qquad [4]$$

$$\frac{\theta_{m+1,\,n+1} - \theta_{m,\,n+1}}{\triangle x} \quad ; \quad \frac{\theta_{m,\,n+1} - \theta_{m-1,\,n+1}}{\triangle x} \qquad [5]$$

$$\frac{\theta_{m+1,\,n+\frac{1}{2}} - \theta_{m,\,n+\frac{1}{2}}}{\triangle x} \quad ; \quad \frac{\theta_{m,\,n+\frac{1}{2}} - \theta_{m-1,\,n+\frac{1}{2}}}{\triangle x} \qquad [6]$$

where $$\theta_{j,\,k+\frac{1}{2}} = \frac{\theta_{j,\,k+1} + \theta_{j,\,k}}{2} \qquad [7]$$

The formulas [4] obviously lead to equation [2] when the second difference is formed, while formulas [5] and [6] lead to

$$\frac{\theta_{m,\,n+1} - \theta_{m,\,n}}{\triangle t} = \propto \frac{\theta_{m+1,\,n+1} - 2\theta_{m,\,n+1} + \theta_{m-1,\,n+1}}{(\triangle x)^2} \qquad [8]$$

$$\frac{\theta_{m,\,n+1} - \theta_{m,\,n}}{\triangle t} = \propto \frac{\theta_{m+1,\,n+\frac{1}{2}} - 2\theta_{m,\,n+\frac{1}{2}} + \theta_{m-1,\,n+\frac{1}{2}}}{(\triangle x)^2} \qquad [9]$$

It is seen that in formulas [8] and [9] the future temperatures occur in implicit alegbraic equations and are therefore not solved as readily as formula [2]. The advantage to these implicit methods, however, is that they are stable for all M values (3). Throughout the remainder of this paper, formula [9] will be called the *implicit substitution*.

In order to illustrate the algebra involved in the implicit solution and the nature of its convergence, a simple problem in unsteady-state heat conduction may now be considered. Figure 1 is a schematic representation of the right-hand half of a homogeneous solid body two feet long, of thermal diffusivity 0.2 ft²/hr, which has been divided into blocks just as in the procedure of Dusinberre (2). The body is at uniform temperature until the temperature of the end faces is suddenly increased by 100F. If, for simplicity, we assume the sides to be perfectly insulated, then the heat flow is one-dimensional, and the analytical solution is known (4).

A heat balance on the first half-block becomes:

$$\frac{\rho c \triangle x \triangle y \triangle z}{2\triangle t} (\theta_{o,\,n+1} - \theta_{o,\,n}) = \frac{k \triangle y \triangle z}{\triangle x} (\theta_{1,\,n+\frac{1}{2}} - \theta_{o,\,n+\frac{1}{2}})$$

Using formula [7] to define $\theta_{j,\,k+\frac{1}{2}}$ and solving for $\theta_{o,\,n+1}$ yields

$$\theta_{o,\,n+1} = \frac{\theta_{1,\,n+1} + \theta_{1,\,n} + \theta_{o,\,n}(M-1)}{M+1} \qquad [10a]$$

Similar heat balances for the remaining blocks yield

$$\theta_{1,\,n+1} = \frac{\theta_{o,\,n+1} + \theta_{2,\,n+1} + \theta_{o,\,n} + \theta_{2,\,n} + 2\theta_{1,\,n}(M-1)}{2(M+1)} \qquad [10b]$$

. . . . . .

$$\theta_{9,\,n+1} = \frac{\theta_{8,\,n+1} + \theta_{8,\,n} + 2\theta_{9,\,n}(M-1) + 200}{2(M+1)} \qquad [10j]$$

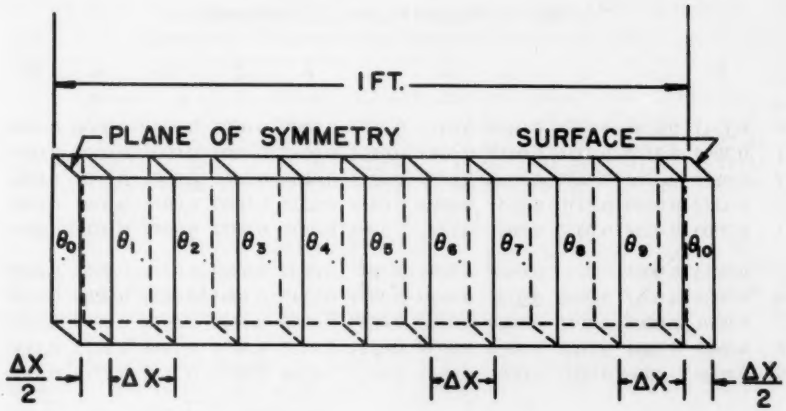


FIGURE 1

PHYSICAL SUBDIVISION OF PLANE PLATE OF FINITE THICKNESS

Now we have ten implicit algebraic equations in ten unknowns, $\theta_{0,\,n+1}$, $\theta_{1,\,n+1}$, etc., which may be solved at each time step as soon as we choose values of M.

It has already been shown (5) that for transient problems of this type (without either temperature-dependent properties or temperature-dependent heat generation), the linear algebraic equations [10] may be solved by successive substitution in the course of the numerical computation. However, if several steps (not necessarily consecutive) are to be carried out with the same M value, it will be advantageous to solve equations [10] algebraically so the future temperatures are explicitly stated. After this is done, the computation of one time step may be performed with a desk machine almost as readily as with the conventional explicit equations [3], while the total amount of computation may be much less than with equations [3] because of the longer time steps.

This procedure of solving for the future temperatures explicitly is especially useful when a problem must be worked repeatedly with changes of certain parameters each time. In such cases, the same basic equations and the same M values will most likely be used over and over. In many practical examples, also, changes of properties, heat generation and boundary conditions with temperature may be handled with equations obtained in this manner, because such variations are usually secondary effects and may be small over each time step.

TABLE 1. Coefficients C_{mj} of $\theta_{m,\,n}$ in Equation 13

j:	0	1	2	3	4	5	6	7	8	9	10
m											
0	0.1547	0.6188	0.1658	0.0444	0.0119	0.0032	0.0009	0.0002	0.0001	0.0000	0.0000
1	0.3094	0.2376	0.3316	0.0889	0.0238	0.0064	0.0017	0.0005	0.0001	0.0000	0.0000
2	0.0829	0.3316	0.1607	0.3110	0.0833	0.0223	0.0060	0.0016	0.0004	0.0001	0.0001
3	0.0222	0.0889	0.3110	0.1551	0.3095	0.0829	0.0222	0.0060	0.0016	0.0004	0.0002
4	0.0060	0.0238	0.0833	0.3095	0.1547	0.3094	0.0829	0.0222	0.0059	0.0015	0.0007
5	0.0016	0.0064	0.0223	0.0829	0.3094	0.1547	0.3094	0.0829	0.0221	0.0055	0.0028
6	0.0004	0.0017	0.0060	0.0222	0.0829	0.3094	0.1547	0.3093	0.0825	0.0206	0.0103
7	0.0001	0.0005	0.0016	0.0060	0.0222	0.0829	0.3093	0.1543	0.3078	0.0769	0.0385
8	0.0000	0.0001	0.0004	0.0016	0.0059	0.0221	0.0825	0.3078	0.1488	0.2872	0.1436
9	0.0000	0.0000	0.0001	0.0004	0.0015	0.0055	0.0206	0.0770	0.2872	0.0718	0.5359

Admittedly choosing the simplest example, $M = 1$, for an illustration, equations [10] may be solved explicitly for $\theta_{m,\,n+1}$ $(m = 0, 1, \ldots, 9)$ in terms of the known temperature differences $\theta_{m,\,n}$ and θ_{10}, the latter being constant for all n. If the calculation is to be carried to two decimal places, any term, $b\theta_{m,\,n}$, may be discarded for $b \leq 0.00005$, since $\theta_{m,\,n} \angle 100F$. First, the expression for $\theta_{0,\,n+1}$, equation [10a], is substituted into [10b], giving an expression for $\theta_{1,\,n+1}$ in terms of $\theta_{2,\,n+1}$ and of known present temperatures. Then this is substituted into [10c], and so on, until there are obtained nine linear algebraic equations of the form

$$\theta_{m,\,n+1} = a_m\theta_{m+1,\,n+1} + \sum_{i=0}^{9} b_{m,\,i}\theta_{i,\,n} \qquad (m = 0, 1, \ldots, 8) \qquad [11]$$

and one equation of the form

$$\theta_{9,\,n+1} = \sum_{j=0}^{10} C_j\theta_{j,\,n} \qquad (m = 0, 1, 2, \ldots, 9) \qquad [12]$$

Now $\theta_{8,\,n+1}$ may be found as an explicit function of the $\theta_{m,\,n}$ by the substitution of equation [12] back into equation [11], $m = 8$, and $\theta_{7,\,n+1}$, $\theta_{6,\,n+1}$, $\ldots$, $\theta_{0,\,n+1}$ may be obtained in similar fashion.

The resulting equations, with $M = 1$, are of the form

$$\theta_{m,\,n+1} = \sum_{j=0}^{10} C_{mj}\theta_{j,\,n} \qquad (m = 0, 1, 2, \ldots, 9) \qquad [13]$$

where the C_{mj} are given in Table 1. These equations will be used later in advancing the numerical solution of the example from 0.15 to 0.30 hrs. (See Table 3 and Figure 4.)

TABLE 2. Comparison Between Temperatures Obtained at 0.15 Hours Showing Convergence With Increasing Fineness of Space-Time Mesh

	$\Delta x = 0.1$ ft							
	M=1/3	M=2/3	M=1	M=4/3	M=5/3	M=2	M=7/3	θ_{ma}
θ_6.....	8.31	9.89	10.95	12.26	10.61	10.62	10.66	10.23
θ_7.....	18.40	22.22	23.77	23.59	22.31	22.28	22.29	22.03
θ_8.....	40.76	44.43	44.10	42.52	41.50	41.44	41.42	41.43
θ_9.....	90.29	66.66	69.80	68.93	68.30	68.25	68.22	68.34
	$\Delta x = 0.2$ ft							
	M=4/3	M=8/3	M=4	M=16/3				θ_{ma}
θ^*_6.....	10.26	11.68	11.81	11.86				10.23
θ^*_8.....	45.06	42.05	41.64	41.51				41.43

First, however, the solution for 0.15 hrs. at the point numbered "9" in Figure 1, located 0.9 foot to the right of the plane of symmetry, is shown in Figure 2 according to both methods of numerical calculation. With the explicit formula [3], an M value of 5/3 produced a marked oscillation, while even for M = 2 (the Binder-Schmidt solution) an oscillation is still very much in evidence. Only when the modulus is increased to 7/3 is this practically damped out. With the implicit method, on the other hand, the solution for M = 5/3 is almost identical to the analytical solution, while even for smaller M (not shown) there is no tendency toward an oscillation. In the latter case, however, the approximation of even the implicit solution becomes poorer (though better than the explicit) because of truncation error, which will now be discussed.

As previously mentioned, convergence or truncation error arises because of the substitution of a finite mesh size in time and space for the infinitesimally small divisions attained in an analytical solution. In the present example, with a space subdivision as shown in Figure 1 ($\triangle x = 0.1$ ft.), the computation has been carried out for various M values to show the effect of changing the size of time step. These temperature differences, θ_6, θ_7, θ_8 and θ_9, are plotted against M in Figure 3. Also shown are the temperature differences, θ^*_6 and θ^*_8, which are obtained by a different length subdivision, $\triangle x = 0.2$ ft. Table 2 compares the temperatures obtained from these calculations with the analytical solution at the same points. For a given $\triangle x$, it is seen that a finer time subdivision (larger M) causes the numerical solution to approach a limit, while the nearness of this limit to the analytical solution is increased by a finer space subdivision. The practical importance of these observations is that the computer can both estimate the truncation error and justify his choice of a mesh size by repeating part of the calculations with a finer mesh and then comparing the solutions.

With the stability limitation, $M \geq 2$, removed, it is usually possible to increase the size of time step as the solution progresses. Using the temperature differences at 0.15 hr. already obtained with M = 5/3 in equations [10], the problem has been completed to 5 hours in 13 steps according to Table 3, with the results shown in Figure 4. For the same total problem time, the Binder-Schmidt solution would have required 200 steps[3] and would have yielded temperature differences which were not nearly as close to the analytical solution, as indicated by Figure 2.

[3] Professor G. M. Dusinberre (7) has pointed out that in an example like the present one, the explicit solution could be greatly shortened by using a coarser network when the time is long. This point is well taken, of course, but it is not always possible to apply this short-cut.

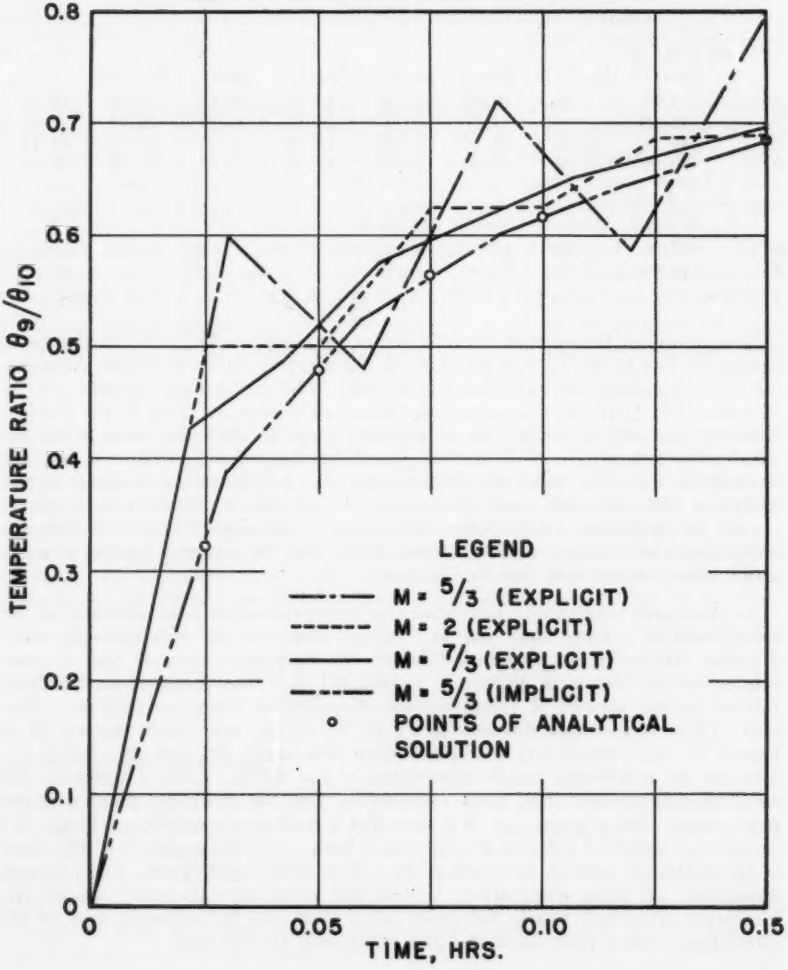
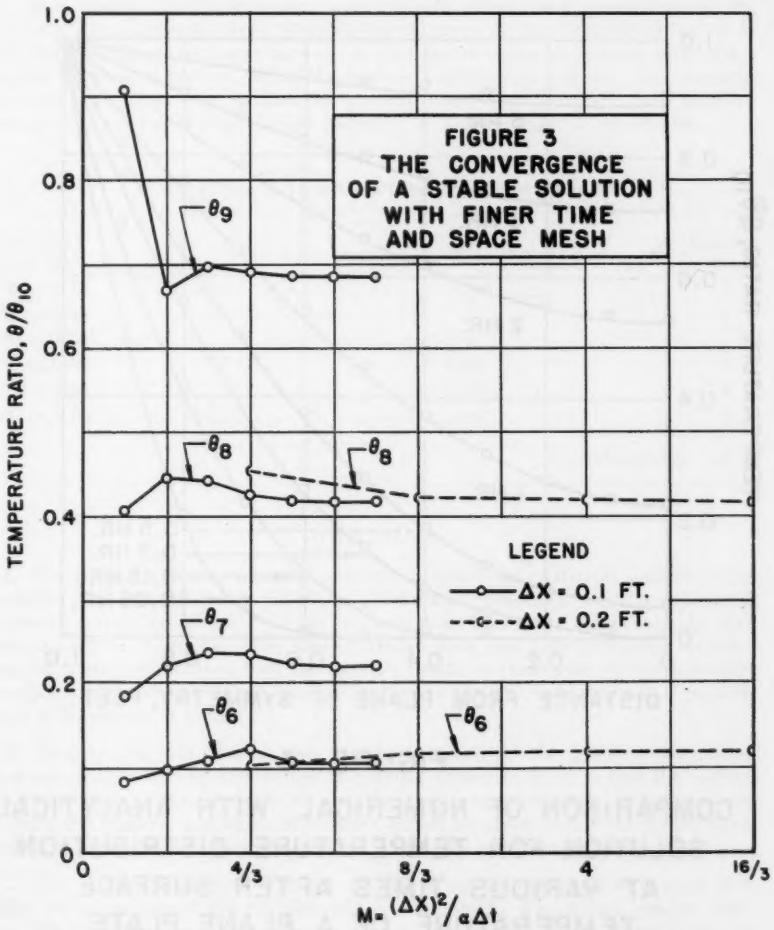


FIGURE 2

STABLE AND UNSTABLE SOLUTIONS FOR TEMPERATURE VARIATION WITH TIME AT ONE POINT IN A PLANE PLATE OF FINITE THICKNESS



It is apparent that the finite difference substitution just described may be applied to more complicated cases with time-dependent boundary conditions, cylindrical or spherical coordinates, composite structure, etc. For example, Crank and Nicolson (6) used an iterative process to solve the implicit equations in a problem in which the internal heat generation varied exponentially with temperature. Generally speaking, the techniques which have been developed for handling various complex cases with the explicit substitution will be applicable as well to the method described herein. The reader is referred to Professor Dusinberre's text on the subject (2).

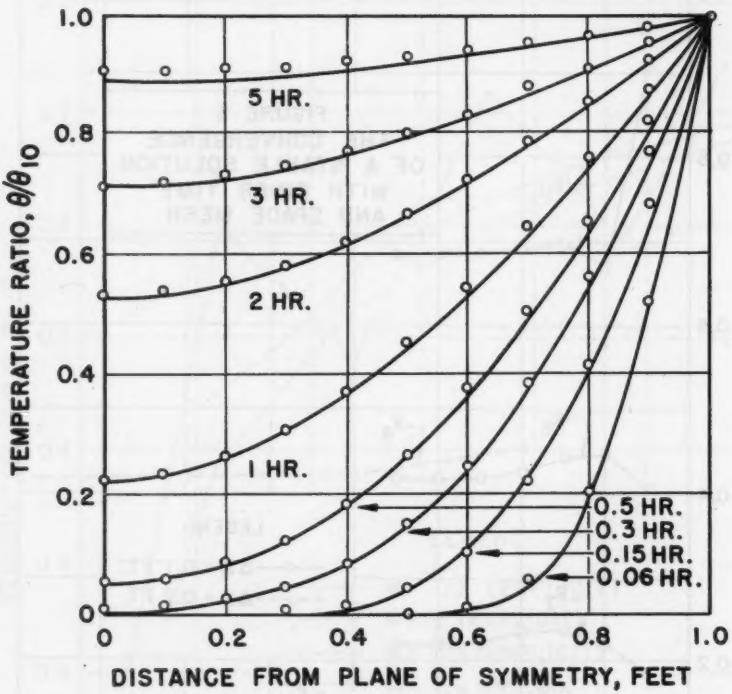


FIGURE 4

COMPARISON OF NUMERICAL WITH ANALYTICAL SOLUTION FOR TEMPERATURE DISTRIBUTION AT VARIOUS TIMES AFTER SURFACE TEMPERATURE OF A PLANE PLATE IS INCREASED BY 100F

Finally, it would be well to point out that the example chosen in this paper to illustrate the implicit finite difference substitution could have been solved readily by the conventional method. The choice was based on a desire for a simple problem with an easily computed analytical solution, rather than for a case where the implicit method would be outstandingly superior to earlier methods. Such a case

has been described (5), however, with time-dependent heat generation in the core of a thin composite plate. Because the thickness in the direction of heat flow was small, the space grid was necessarily fine and the time steps quite small for a modulus of two or greater. With the implicit substitution, however, the computation was reduced greatly, so that the problem could be solved on a desk machine instead of requiring a large digital computer as did the explicit substitution.

TABLE 3. Size of Time Steps Used in Different Solution

Problem time, hrs.	M	Number of Steps
0 to 0.15	5/3	5
0.15 to 0.30	1	3
0.30 to 0.50	1/4	1
0.50 to 1.00	1/10	1
1.00 to 3.00	1/20	2
3.00 to 5.00	1/40	1
	Total time steps	13

CONCLUSIONS

1. For transient heat conduction problems in which an analytical solution is not available, the implicit finite difference substitution described in this paper will frequently offer considerable saving in computing time over the previously used explicit method. Since one time step calculated on a desk-type computing machine requires more computation with the implicit equations than with the same number of explicit equations, however, this advantage is realized only when it is possible to go to fractional M values.

2. Usually, the size of time step may be increased as the problem progresses. However, as few different M values as possible should be used, so that the implicit equations may be solved explicitly for the future temperatures. When this can be done, the numerical calculation becomes almost as simple as for the conventional explicit substitution. (Compare equation [13] with equation [3].)

3. The implicit substitution is not subject to the limitation $M \geqq 2$, since it is stable for all values of the modulus M, however small. There does remain, however, the consideration of convergence error to limit the values of M which may be used.

4. In the region where either method may be used, around $M = 2$, the implicit method shows a markedly smaller truncation error for the same mesh size.

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THE INFLUENCE OF SULPHURIC ACID UPON THE DEW POINT OF COMBUSTION GASES

GEORGE A. FEARN, JR. AND COMMANDER WILLIAM TESSIN, USN

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INTRODUCTION

Thermodynamic considerations show the desirability of the use of economizers and air pre-heaters on boilers, and heat recovery devices on internal combustion engines. Condensate formed by the subsequent cooling of the combustion gases below the dew point has been a source of difficulty in the operation of such equipment.

The corrosive effects of condensation have been observed when using sulphur bearing fuels. Condensation has appeared when the bulk gas temperatures are higher than the computed water dew point has predicted, and severe corrosive attack on various components has been frequent. Analysis of the condensate has usually shown it to be a weak solution of sulphuric acid.

It is our object to show how the highest dew point of the combustion gases from sulphur bearing fuels may be predicted.

VAPOR-LIQUID EQUILIBRIUM DATA

The behavior of sulphuric acid vapors in the flue gases may be illustrated as in Figure 1. The upper curve shows the condensation temperature as a function of the vapor composition and the lower curve shows the liquid boiling point as a function of composition. The diagram is applicable to a single total pressure; similar diagrams apply at other pressures. For a pure component, the boiling point and condensing temperature are the same. The boiling point of constituent B is t_B and that of A is t_A.

To illustrate the use of such a diagram, assume a vapor of composition 20%B, 80%A. The first condensate appears at t_1, the dew point; the composition of the condensate is rich in component B; namely, 70%B, 30%A. At a temperature as t_2 the vapor composition has changed to 6%B, 94%A, while that of the condensate changed to 40%B, 60%A. At a temperature as t_3, the last vapor present, has a composition 2%B, 98%A, while the liquid has the original composition of the vapor; namely, 20%B, 80%A. In the condensation process, therefore, the vapor composition changes from 20%B, 80%A to 2%B, 98%A; that of the condensate changes from 70%B, 30%A to 20%B, 80%A.

The above discussions may be extended when inert gases are mixed with the vapors. However, when cooling below a temperature as t_3, some of the condensables will remain in the vapor state to saturate the inert gases. The liquid composition will then change as the partial pressure of the vapor changes.

To draw a diagram as Figure 1, it is evident that the composition of the vapor in equilibrium with the liquid is required for all pressures, temperatures and concentrations.

REPRESENTATION OF VAPOR-LIQUID EQUILIBRIUM

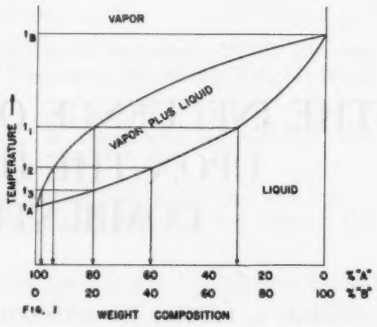

FIG. 1

The vapor pressure of sulphuric acid solutions has been tabulated in Rogers (1)* including data for an azeotropic acid-water mixture. This mixture, 98.3% acid, 1.7% water by weight, has the property that the vapor composition is the same as the liquid; hence, it behaves as a pure component.

Thomas and Barker (2) made measurements of the vapor pressures of sulphuric acid-water solutions having high acid concentrations. They determined the composition of the vapor assuming no dissociation in the vapor.

Taylor (3) and Francis (4) made measurements of the dew points of air-water-acid mixtures at atmospheric pressures. Francis made calculations to show the influence of gases normally found in combustion products on the water dew point. His data show that the gases may be treated as diluents which fix the partial pressure of the acid-water system and have practically no effect on the dew point.

The variation of the boiling point with pressure for various concentrations

* Numbers in parentheses refer to titles in the Bibliography.

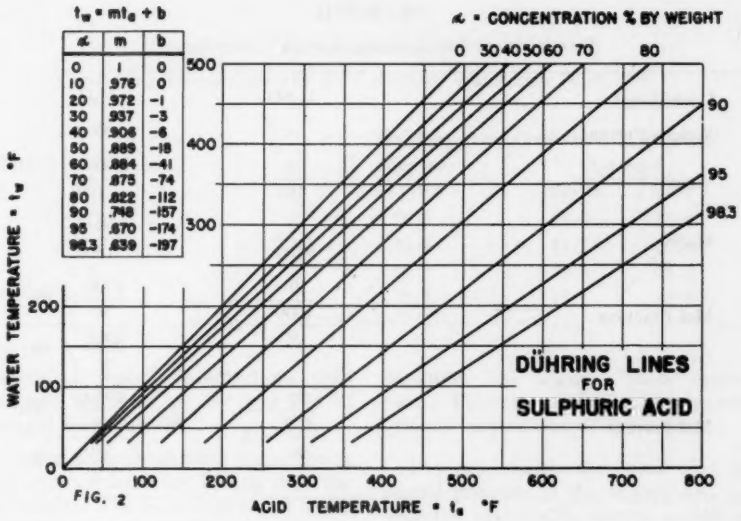

FIG. 2

of acid-water solutions is conveniently described by the use of Dühring lines (5). The boiling point of a mixture may be determined with respect to that of a known reference liquid. Figure 2 has been constructed for the sulphuric acid-water system with water as the reference. For example, water boils at 212° F. at standard conditions; a 50% by weight acid-water mixture boils at 259° F. at the same pressure. In like manner, if the pressure is such that water boils at 150° F., then a 70% by weight acid-water mixture boils at 257° F.

TABLE I

Sulphuric Acid-Water Boiling Point Data
(Applicable to Figure 2)

	$t_w = mt_a + b$	
Acid Concentration % by Weight	*Slope, m*	*Constant, b*
0	1.000	0
10	0.976	0
20	0.972	−1
30	0.937	−3
40	0.906	−6
50	0.889	−18
60	0.884	−41
70	0.875	−74
80	0.822	−112
90	0.748	−157
95	0.670	−174
98.3	0.639	−197

The Dühring lines are assumed to be straight. The results in Table I have been calculated from data appearing in Rogers and the International Critical Tables (6).

The data enables construction of the liquid boiling line (as the lower line of Figure 1) for various pressures and for acid concentrations to 98.3% by weight. Consequently, these data are applicable to combustion gases from usual fuels.

The equilibrium relations between vapor composition and liquid composition are shown in Figure 3. These data were obtained at atmospheric pressure and less by Thomas and Barker, Taylor, and Francis. With the aid of Figure 2 and the dew point-vapor composition data of Taylor and Francis, we com-

TABLE II

Conversion Factors

Constituent	H_2SO_4	H_2O
Weight Percent	$\times$	$100-\times$
Weight Fraction	$\frac{\times}{100}$	$\frac{100-\times}{100}$
Mols	$\frac{\times}{9800}$	$\frac{100-\times}{1800}$
Mol Fraction	$\frac{9}{\frac{4900}{\times}-40}$	$\frac{\frac{4900}{\times}-49}{\frac{4900}{\times}-40}$
Mol Percent	$\frac{90}{\frac{490}{\times}-4}$	$\frac{\frac{49000}{\times}-490}{\frac{490}{\times}-4}$

puted the corresponding equilibrium liquids. Conversion factors for ease in computation are given in Table II.

It is assumed that the data in Figure 3 apply to pressures and temperatures other than those at which obtained. Study of the Thomas and Barker data shows that the change in vapor composition with temperature for a given liquid composition is negligible.

Abel (7) used a method of calculating the liquid-vapor equilibrium based on thermodynamic procedures. His results are in agreement with the data of Thomas and Barker, Taylor, Francis, and Figure 3, the greater variations oc-

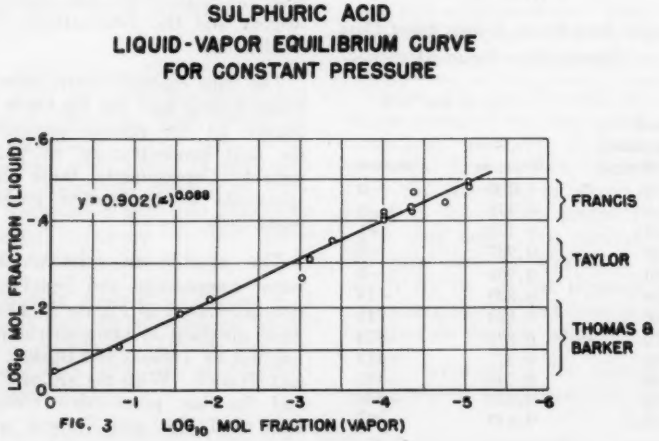

FIG. 3

TABLE III

Comparison of Dew Point and Condensate Strength

Condensing Temperature 243° F., Calculated Water Dew Point, 109° F.

Dew Point °F.	*Sulphuric Acid Condensate, % by weight*		
	Observed	*Computed*	
	Taylor	Taylor	Figure 2
320	76.0	75.3	75.6
347	74.9	75.1	75.6
374	75.3	75.5	75.6
401	75.5	75.1	75.6

curring at vapor concentrations with acid mol fractions of 10^{-5} and less at elevated temperatures.

Taylor also performed experiments with acid vapors in air having differing dew points. The partial pressures of the acid vapors were nearly constant. He measured the strength of condensate and also computed it from vapor pressure data. His calculated and measured results are in excellent agreement, shown in Table III.

The composition of the condensing liquid is dependent upon temperature alone, at constant pressure, once condensation has begun. These experiments, therefore, indicate that dynamic systems may behave as static ones.

The experiments also show that the partial pressure of the vapors does not decrease appreciably during condensation even when the difference between the dew point and the condensing temperature is as large as 158° F.; as for example with his strongest acid vapor—approximately 0.24% acid by weight. It is evident that significant changes in partial pressures may not occur above a temperature as that corresponding to t_3 of Figure 1.

THE EQUILIBRIUM DIAGRAM

The sulphuric acid-water equilibrium diagram for acid vapor condensables at a partial pressure of 76 mm Hg, approximating marine boiler operating conditions, is shown in Figure 4. The figure illustrates how relatively minute amounts of acid in the vapor cause a large dew point elevation and the subsequent high acid strength of the initial condensate. Figure 4 was constructed from the data of Figures 2 and 3.

In many cases, construction of the diagram (Figure 4) is unnecessary. The partial pressures of the acid vapors may be considered as that of the water in the vapor. From the Thomas and Barker data, for example, it may be seen that with a liquid composition of 89.3% acid, the vapor composition is only 6.2% acid by weight or 1.2 mol percent. Hence, for relatively high acid concentrations in the liquid, the equilibrium vapor is almost all water, except near the azeotropic mixture.

The strength of the acid deposited may be obtained from the intersection of the water dew point corresponding to the partial pressure and that of the observed dew point in Figure 2. This may be illustrated with the Thomas and Barker data as follows: their boiling point for 89.3% acid (by weight) is

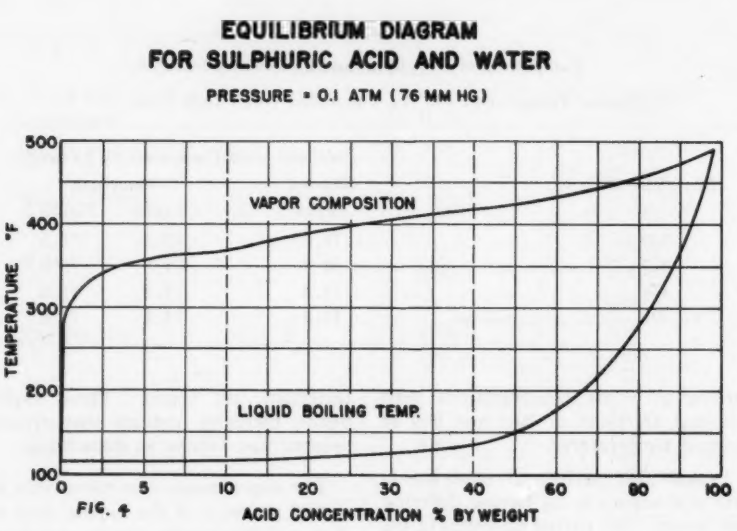

FIG. 4

494° F. at standard pressure; that of water is 212° F. Using linear interpolation, the intersection of 212° F. and 494° F. in Figure 2 shows the acid strength of the liquid to be 90.1% by weight.

The dew point of a system of gases of known composition and partial pressures may also be predicted without the diagram. The composition of the liquid in equilibrium with a given vapor at the dew point is given in Figure 3. The intersection of the determined liquid composition with the water dew point in Figure 2 yields the boiling point of the liquid which is the dew point of the vapors.

It should be noted that the bulk of the gas stream need not be cooled to the dew point to cause condensation. A cold surface in way of the gases may collect condensate, the rate of collection being governed by the laws of diffusion.

If the bulk of the gas is cooled below the dew point, then the partial pressures of the vapors are reduced below that of the initial dew point. However, the amount of condensate may be calculated by assuming that the gas contains water vapors only, and that the partial pressures in the system do not change appreciably until the pure water dew point is reached.

THE AVAILABILITY OF SULPHURIC ACID

The data presented in the previous sections are applicable when the composition of the gases is known. Francis has made studies to show that sulphuric acid alone could adequately explain the high dew points of flue gas which have been measured. It was mentioned that the usual constituents of flue gas have negligible effect on the dew point as long as the concentration and partial pressure of the acid-water mixture is not changed. The only continuous source of sulphur in the combustion gases is from the fuel. The highest

possible concentration and corresponding dew point, therefore, may be computed from the fuel analysis, the humidity of the combustion air, and the fuel-air ratio.

Such a computation assumes complete conversion of the sulphur in the fuel to sulphur trioxide and subsequent mixing with the water vapor in the gas stream. It also assumes that all such converted sulphur remains apart from other combustion products or materials in the gas stream. In the practical case, however, such assumptions may be invalid. A variable, to be spoken of as "availability," is present for each and every combustion application. We choose to define availability as the ratio of mols of sulphuric acid in the gas stream at the place of condensation to the mols of sulphur fired, or

$$\text{Availability} = \frac{\text{mols } H_2SO_4}{\text{mols S}}$$

The availability is dependent upon (1) the oxidation of sulphur and its compounds to sulphur dioxide, (2) conversion of the dioxide to trioxide, (3) adsorption of the dioxide and/or the trioxide on solid surfaces, (4) combination of the oxides with alkali metals in the ash, (5) combination of sulphur trioxide with water vapor in the gas stream, and (6) dissociation of acid vapors.

Manning (8) lists a sequence of reactions involved in the deposition of a sulphuric acid film from a flue gas as follows:

$$SO_2 + \tfrac{1}{2}O_2 \rightarrow SO_3, \text{ slow except above } 1830^\circ \text{ F.} \quad (1)$$

$$SO_3 \text{ (gas)} + H_2O \text{ (gas)} \rightarrow H_2SO_4 \text{ (gas), fast} \quad (2)$$

$$H_2SO_4 \text{ (gas)} + xH_2O \text{ (gas)} \rightarrow H_2SO_4 \text{ (liquid solution), fast} \quad (3)$$

In the normal combustion process rapid vaporization, high temperatures, and reasonable mixing of the reactants provide conditions for rapid oxidation of sulphur and its compounds in the fuel to SO_2.

The governing condition is reaction (1). An extensive literature exists with respect to the speed of reaction and the equilibrium conversion. In general, the speed of reaction is rapid at high temperatures but equilibrium conversion to the trioxide is small; the speed of reaction is slow at low temperatures but greater conversion occurs.

Manning summarizes reaction (1) as follows: "In the absence of a catalyst, the actual conversion of SO_2 to SO_3 in a flue gas would be small (½—1%) since at the temperature at which reaction was rapid, equilibrium conversion is small. If the gas met a catalyst, the reaction rate would be high at low temperature, and since the equilibrium conversion is high at low temperatures, the actual conversion would be increased." Data in Rogers shows that conversion is complete at 570° F. with a gas containing 7% SO_2, 14% O_2, and 79% N_2, by volume, at atmospheric pressure.

The presence of catalysts in the flue gas stream has been studied. Rogers lists the catalysts used in the manufacture of sulphuric acid; predominantly platinum and vanadium types in the contact process and nitrogen oxides in the chamber process. Manning also states that Fe_2O_3 has little effect in the contact process below 750° F. and maximum effect at about 1100° F. Rylands and Jenkinson (9) state: "It has been known for many years that iron sulphate is not only deliquescent, but is also a powerful catalytic agent, capable of converting SO_2 to SO_3."

Experiments by Harlow (10) show: (a) flue gases passed over-heated, rusty

mild steel scrap had a higher dew point (attributable to conversion) after exposure than before, greatest conversion occurring at about 1100° F., and almost none below 800° F.; (b) steel coated with pulverized ash was not effective as a catalyst; and (c), rust, as Fe_2O_3, is effective as a catalyst while rust, as Fe_3O_4, is not. A major conclusion by Harlow is that the metal temperatures of superheater tubes with their coating of metallic oxides would be conducive to conversion.

Rogers also has a discussion of the effect of pressure showing that higher conversion may be expected at higher pressures.

Corbett, Flint and Littlejohn (11) describe acid dew point measurements made in the gases of coal fired boilers. Their measurements show that a difference may be expected with a given fuel dependent on the method of firing, pulverized or grate fired; and that the cleanliness of the firesides does not affect the dew point.

The American Gas Association (12) refers to experiments by Johnstone and Maconachie. These results are summarized as follows:

Fuel	$R = \frac{SO_3}{SO_2}$, *by volume*
Pulverized Coal	0.008
Stoker fired coal	0.016–0.029
Petroleum residues and natural gas	0.137
City gas with 95% excess air	0.28

If all the sulphur fired is oxidized and there is sufficient water vapor in the gases to combine with all the SO_3 to form a mixture less concentrated than the azeotropic, then the values, R, given above may be compared with the availability ratio by the equation:

$$\text{Availability} = \frac{R}{1 + R}.$$

An analysis of the condensate from a particular installation has indicated that 70% of the sulphur fired in a diesel fuel appeared in the condensate. This would indicate an availability ratio of 0.70. However, direct observation of the equipment involved and study of related factors shows that such an availability could not occur. It is probable, therefore, that the vapors in the gas stream are highly dissociated. The actual concentration of free sulphuric acid would then be low. In this event, a low availability would be expected, with a corresponding reduction in the dew point. However, once condensation has started, the dissociation equilibrium would be disturbed so as to maintain the vapor concentration at some value approximating the initial un-dissociated concentration. Consequently, it may be possible to recover in the condensate, nearly all the sulphur fired, even though the availability ratio is very low. This effect can result in a corrosion "band" within a heat exchanger in which the extent of corrosion is unchanged. This band location would shift with load.

The difference between the results with pulverized and stoker fired fuels may be due to adsorption of the sulphur oxides by ash particles. If the dioxide is adsorbed, then expected conversion may be diminished with resultant loss of availability. If the trioxide is adsorbed, then loss of availability occurs after conversion. Soot deposits having 6% of the sample weight as free acid have been obtained from oil fired Naval boilers.

The influence of alkali metals in the fuel upon availability may be judged

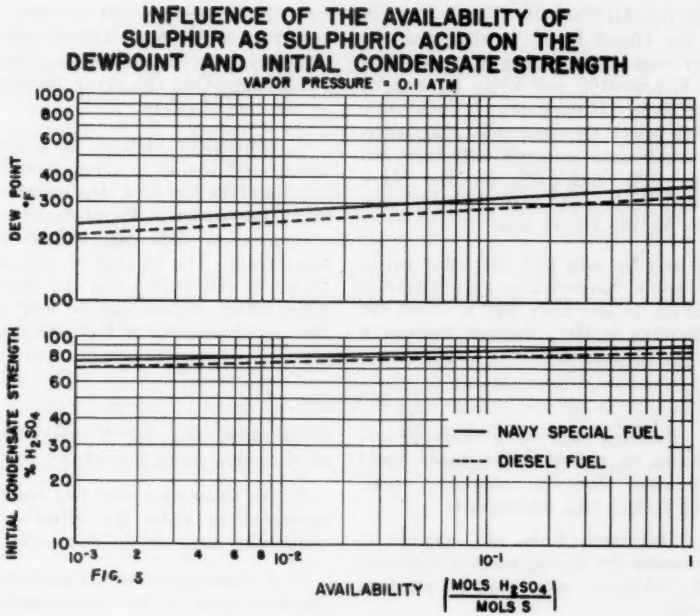

FIG. 5

from an analysis of fireside deposits. Such deposits collected after firing fuel oils contaminated with sea water contain relatively large amounts of sodium sulphate. The high deposition temperature of such salts could reduce the number of sulphate ions available for possible deposition at the acid dew point.

Reaction (2) is listed as fast, and according to Taylor, the equilibrium conditions permit the reaction to be complete to the right below 428° F. Reaction (3) is also fast. The experiments of Taylor show that equilibrium is rapidly established.

The observations and measurements presented have the effect of lowering the dew point as calculated above. The amount of reduction is dependent upon the availability. With a known availability ratio, and the calculated maximum acid content of the flue gas for a particular combustion process, the dew point of the gases along with the strength of the initial condensate may be determined from an equilibrium diagram such as Figure 4.

The change of dew point and initial acid condensate strength with availability is shown in Figure 5. The data for construction of the figure are:

a. Navy Special Fuel; 86.5%C, 11.1%H, 2.4%S by weight.

b. Navy Specification Diesel Fuel; 86.0%C, 13.6%H, 0.4%S by weight.

c. Atmospheric humidity arbitrarily chosen to fix the partial pressure of condensables at 0.1 atm.

At unit availability, for the example chosen, the strength of acid in the condensables is 5.8% by weight for the

Navy Special Fuel and 0.9% by weight for the Diesel Fuel. In this case, the initial condensate strengths, from Figure 5, are 91% and 85%, by weight, respectively. If the gases are sufficiently cooled below the dew point, therefore, the condensate strength will vary between 91% and 5.8% for the Navy Special fuel, and between 85% and 0.9% for the Diesel fuel.

It may be seen that the reduction in dew point, compared to an availability of unity, is less than 100°F. when the availability is 10^{-2}. In new designs it may be necessary to assume this reduction to be small, and to base calculations on maximum availability, recognizing that the error involved is on the side of safety.

A convenient method to determine the availability in a given installation combines the use of a dew point meter and a knowledge of the highest possible concentration of the acid vapors in the gas stream. The amount of acid in the vapors is relatively small and the computed water content may be used to fix the partial pressure of the condensables.

SUMMARY

1. Existing data were analyzed and a means to correlate the vapor-liquid equilibrium for the sulphuric acid-water system was determined.

2. Dühring's Rule was applied to extrapolate the boiling point of sulphuric acid solutions over large pressure ranges.

3. Existing data were studied to determine the factors which influence the conversion of sulphur in a fuel to sulphuric acid in the combustion products. These factors were used to define an availability ratio which could be applied to dew point prediction.

4. An example using two fuels was presented to show the effect of the availability ratio on the dew point.

5. A consequence of the prediction of the dew point is the determination of the strength of acid deposited at the dew point.

6. In new designs, it may be necessary to base calculations on maximum availability.

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LOW-HYDROGEN WELDING RODS

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INFLUENCE OF THE COATING OF THE ELECTRODE ON THE GAS CONTENT OF THE DEPOSITED METAL

In most countries of the world only coated electrodes are used for electric arc welding, particularly for welding in air. The chief function of the coating is the protection of the molten metal from the oxygen and nitrogen in the air. Its second and nearly as important function is the evolution of sufficient gas for the globules, developed during the welding process at the end of the electrode, to be driven out with great force, giving rapid transfer of the metal to the work piece and good penetration (even in the case of "overhead" welding).

The coating of electrodes always contains metal oxides. Should these metal oxides easily yield large quantities of oxygen to the molten metal, the abovementioned favorable function of the coating, viz., that of protecting the metal from oxygen (and nitrogen attack) would be illusory. By using very stable oxides only and by adding reducing metal powders to the coating, the latter was improved to the point of yielding a minimum quantity of oxygen to the weld metal. However the greater the success in combating the evil of oxygen absorption, the nearer becomes the incidence of another nuisance, viz., the absorption of considerable quantities of hydrogen.

The combination of compounds contained in the coating of an electrode releases water vapor on heating. This water vapor enters the arc atmosphere and is in contact with the molten metal during the welding process. Hydrogen and oxygen being soluble in this metal to a certain extent, the following equilibrium is ultimately approximated:

$$H_2O \rightleftarrows 2[H] + [O] \qquad (1)$$

The square brackets indicate the hydrogen and oxygen in the metal in the dissolved state. (H and O have been used as symbols instead of H_2 and O_2 because hydrogen and oxygen are present in the metal in the atomic and not in the molecular state.) In equilibrium—depending on the temperature T—a simple relationship holds approximately, between the percentages of hydrogen and oxygen in the metal and the pressure $p(H_2O)$ of the water vapor outside. This relationship is the following:

$$\frac{[\%H]^2 \times [\%O]}{p(H_2O)} = C(T) \qquad (2)$$

showing that the smaller the oxygen content of the metal and the larger the pressure of water vapor, the larger is the hydrogen absorption by the metal.[1]

[1] The state of equilibrium to which eq. 2 is applicable is never completely attained during the welding process. Nevertheless the formula will be useful for the following semiquantitative discussion.

It is indeed a fact that on improvement of the electrode coatings with regard to the release of oxygen to the metal, the hydrogen absorption by the metal increased automatically at an unchanged water vapor content of the arc atmosphere. This was attended by various disagreeable phenomena.

DETRIMENTAL ACTION OF HYDROGEN

Hydrogen is absorbed by the molten metal during the welding process. The solubility of hydrogen in iron diminishes with decreasing temperature; at the solidification point it even drops abruptly. Thus the absorbed hydrogen will be partly released again during the cooling process. If the metal is still liquid the excess gas can leave it in two ways: (1) gas bubbles may form in the liquid metal and rise to the surface under the influence of the hydrostatic pressure; (2) the atoms may diffuse to the outer surface and recombine to form molecules.

We have already discussed extensively in this review the effect of these two processes on the welding process itself. In some circumstances, e.g., when relatively large quantities of sulfur are present in the metal, the formation of gas bubbles during the cooling process may cause porosity of the weld. The article cited under Reference 1 gives more details on the influence of sulfur.

As soon as the deposited metal has completely solidified, further release of hydrogen can only be effected via the second process: diffusion of hydrogen atoms through the metal and subsequent recombination at the surface to molecules. The thicker the metal from which the gas is to be released and the lower the temperature,[2] the longer the diffusion process will take. Hence, if the metal to be welded is very thick, a large quantity of hydrogen will be retained, in the first place owing to the long distance the atoms have to travel in the diffusion process and in the second place by the rapid cooling caused by the thickness of the metal. In this second process, as in the first one, the presence of sulfur may retard the release of hydrogen still more (2).

The excess hydrogen, left in the metal after the cooling process, can collect under very high pressure in molecular form in internal microscopic or submicroscopic voids. The following may serve to explain this (2). Let us suppose solid iron in equilibrium with hydrogen of 1 atmosphere at 1520° C to cool down so rapidly to room temperature that no hydrogen at all is released. At the temperature of 1520° C about 14 cm^3 hydrogen was dissolved in the atomic form in every hundred grams of iron. At room temperature less than 0.1 cm^3 hydrogen is present in this form per 100 gs of iron in the equilibrium state (with hydrogen at 1 atm outside the iron). However, 14 cm^3 hydrogen are actually still present in the iron after quenching and this corresponds to an external equilibrium pressure of more than 20,000 atmospheres.

The rate of diffusion of hydrogen in iron is still relatively high at room temperature; a considerable quantity of hydrogen will be released after recombination at the outer surface.[3] This process of recombination to molecules will also take place at the surface of each small cavity or included piece of slag in the interior of the metal. Most important of all: at low temperatures the process does not take place at a

[2] This holds good for iron in only one modification, e.g., ferrite, for in austenite the rate of diffusion of hydrogen is smaller.

[3] If a newly made weld is immersed in water, in many cases small gas bubbles will be formed at the surface for a long time.

perceptible rate in the reverse direction since only atoms can diffuse through the metal and since dissociation of hydrogen molecules at the surface is a very slow process at low temperatures. As long as the metal is supersaturated with hydrogen the diffusion to the cavities will proceed, even if the pressure in the cavities rises to very high values. In the case under discussion this pressure can increase to thousands of atmospheres. Welding with normal types of electrode may therefore be expected to lead to the building up of large pressures of hydrogen in tiny voids within the weld. Consequently test bars made from the metal of such a weld show so-called fisheyes on the surface of fracture. These fisheyes show minor holes or inclusions in their center. In these regions the metal could not deform plastically because of the high hydrogen pressure and the stresses developing during the elongation. During the deformation of the test bar this results in brittle fractures on a very small scale in these regions. It was found that the pressure in the micro voids only increase to dangerously high values during the elongation. Hence fisheyes can only be formed after much larger deformation than ever occurs in a construction and therefore cannot adversely influence the strength of the welded joint.

What is much more serious, the presence of much hydrogen under very unfavorable conditions may lead to cracking in or near to the weld. This may happen with electric welding when the carbon content of the steel to be welded is very high. These cracks near the weld can be accounted for as follows: In the region of the weld the metal is heated to the austenite range (γ-iron range) during the welding process; the subsequent rapid cooling can give rise to the formation of martensite (3) (carbon-containing body-centered cubic iron with tetragonal deformation). The attendant changes in volume may in their turn cause the development of cracks of microscopic size. High hydrogen pressures may develop in these cracks unless electrodes of the low-hydrogen type are used, and these may grow into macroscopic cracks in the relatively brittle region around the weld.

Hydrogen may also contribute to cracking of the still hot metal of the cooling weld itself (so-called "hot-cracking") (4). Further discussion of this subject in the present paper would lead us too far.

COATING OF SOME TYPES OF ELECTRODES

It is evident from the preceding sections that the water content of the coating has increased in importance with the decrease of the oxygen transmitted by the coating to the metal. We shall go somewhat deeper into the problem by discussing the chief types of electrodes. They are, respectively:

1. The bare electrode.

2. The dead-soft electrode (completely inorganic coating, chiefly consisting of iron oxides, carbonates and silicates).

3. The mineral-coated electrode with ferromanganese and ferrosilicon added to the coating.

4. The organic electrode containing large quantities of TiO_2 (rutile), although its most characteristic constituents are certain organic compounds.

5. The basic or low-hydrogen electrode, to be discussed later in this paper.

The two first-mentioned types of electrodes (the bare electrode and the dead-soft electrode) are hardly used any more nowadays. With the exception of

Table 1—Hydrogen and Oxygen Contents of the Deposited Metal

Type of electrode	Experimentally found contents			Lower limit of the hydrogen content according to formula (2)	
	Weight % O total	Weight % O as FeO	Weight % H	Weight % H	Cm^3 H_2 per 100 gr iron
Bare	0.25	0.25	——	0.0002	2.5
"Dead-soft"	0.20	0.20	——	0.0010	11.5
"Mineral-coated"	0.12	0.04	0.0015	0.0013[a]	15
"Organic"	0.06	0.004	0.0020	0.0019	21
"Low-hydrogen"	0.03	0.001	0.0007	0.0006	6.5

the last type (the low-hydrogen electrode) all coated electrodes contain substances, e.g., waterglass and organic compounds, which evolve relatively large quantities of water vapor during the heating process. Starting from the equilibrium formula (2), we shall try to compute the hydrogen content of the metal deposited by the various types of welding rods. To do this we shall have to know in the first place the value of the constant $C(T)$ from eq. 2 for about 1540°C, i.e., at a temperature just above the melting point of iron (1539° C). We have pointed out in another paper (5) that at this temperature:

$$C = 1.1 \times 10^{-6},$$

if the water vapor pressure is given in atmospheres and the hydrogen and oxygen content of the metal in weight by percent. Moreover, we shall need two experimental values for each type of welding electrode, viz. the water vapor content of the arc atmosphere and the oxygen content of the liquid metal.

With regard to the latter a difficulty arises because the metal to be welded also contains silicon and manganese, which have a great affinity for oxygen and thus lower the activity of this element in the molten metal. We shall get an upper limit for the hydrogen absorption of the molten metal if we only take into account that percentage of oxygen which on chemical analysis of the deposited metal is found in the form of FeO. On the other hand a lower limit for the hydrogen absorption will be found if the percentage substituted in eq. 2 is the total analytically found oxygen content. However, the latter value should never exceed the saturation content of the molten metal at 1540° C, viz., 0.2% O. Even if more oxygen has actually been absorbed, we should never substitute a greater value since the surplus is not present in the dissolved state, whereas the quantity [% O] in the formula only refers to this state. As a matter of fact the metal absorbs more oxygen than corresponds to the solubility in molten iron if bare electrodes are used (the surplus as an oxide).

We have, basing ourselves on the experiments of Mallett and Rieppel (6), substituted in the formula a value of 0.2 atm for the partial water vapor pressure in the arc atmosphere for all coated electrodes except the low-hydrogen one. For bare electrodes the water vapor content is at the utmost equal to that of the atmosphere, viz., only about 0.01 atmosphere. The same low partial pressure was entered in eq. 2 for the low-hydrogen electrode. We shall discuss this later.

Table 1 gives both the total oxygen percentage and the oxygen present as FeO for the deposited metal of the above-mentioned types of electrode. A third experimentally found content is

given, viz., the hydrogen content of the deposited metal. Moreover, the table contains the lower limit of the hydrogen content calculated with the aid of eq. 2 (see above).

Computation of an upper limit of the hydrogen content in the above-mentioned manner gives values for the two last types of electrodes that correspond to hydrogen pressures considerably higher than 1 atm. In these cases, therefore, calculation of an upper limit would have to be carried out in a slightly different manner. It would lead us too far to discuss the problem more extensively in this paper.

It will be noted that there is fair agreement between the experimentally found values and the calculated lower limits of the hydrogen content. This agreement is surprising since our calculations are but rough. We have not only based ourselves on an assumption which only holds good on approximation, viz., that a state of equilibrium is reached during welding, but—what is of more importance — we have neglected two most important factors, viz., the release of a considerable quantity of hydrogen during the solidifying and cooling process and the absorption of a large quantity of hydrogen in excess of the above calculated lower limit under the influence of silicon and manganese present in the metal. The two faults in our computation apparently counterbalance each other. As a matter of fact the experimentally found hydrogen contents exceed the figure given in the table if the cooling process is extremely rapid, whereas abnormally slow cooling results in smaller hydrogen contents.

It is evident from Table 1 that the improvement of the quality of the weld metal by reducing the oxygen content was at first obtained at the cost of an increase of the hydrogen content. A high oxygen content is so unfavorable that bare electrodes are no longer used in most countries, although the welds produced by using these electrodes have a very low hydrogen content; dead-soft electrodes are only applied when a fine appearance of the bead is of more importance than its mechanical strength. All things considered, the two next types of electrodes, the mineral coated electrode (e.g., the Philips electrodes 50 and Contact 20) and the organic electrode (e.g. the Philips 68 and Contact 18) are important improvements on the two preceding electrodes, but the hydrogen content of the deposited metal has risen to a relatively high level (especially if the organic electrode is used).

With basic electrodes, (e.g., Philips electrodes 36 and 56), a weld can be made containing both little oxygen and little hydrogen. Therefore the use of these more expensive electrodes is often economically justified. We shall now proceed to a discussion of the way in which the favorable properties of these electrodes are obtained.

THE LOW-HYDROGEN ELECTRODE

In principle the oxygen content of the weld metal can be lowered by choosing an electrode coating that produces a slag containing no oxides at all or only very stable oxides. The use of iron oxides should be avoided in the first place. Good results can be obtained with a mixture of stable oxides and fluorides; their proportion in the mixture should be such that the quantity of nitrogen transmitted to the metal is also small (7).

For the weld to have as low a hydrogen content as possible only little water vapor should be evolved by the coating during the welding process. At first sight, one would suppose that this requirement could easily be met by heating the electrodes before the welding process to a temperature that is high

enough for all the chemically bound water to be driven out. However, such a thermal treatment tends to make most electrodes unfit for use since it considerably reduces the development of gas during the welding process; we have already observed that adequate evolution of gas is of primary importance. Moreover, the heat treatment as a rule reduces the mechanical strength of the coating to such a degree that the electrodes can no longer be transported.

However, all requirements can be met by: *(a)* using a coating containing a carefully chosen mixture of substances that evolve gases containing no hydrogen; *(b)* by a well-chosen thermal treatment of the electrodes before delivery. Since chiefly basic oxides are used in the coating, these low-hydrogen welding rods are often called basic electrodes.

Low-hydrogen electrodes manufactured and treated in the way described yield only very little hydrogen during the welding process; the water vapor pressure in the arc atmosphere is as low as in that of bare electrodes, viz., about 0.01 atm; according to eq. 2 this corresponds to the low hydrogen content of the weld of 6.5 cm^3 per 100 gms of iron, already given in Table 1. The various difficulties caused by hydrogen are no longer observed if these electrodes are used.

USE OF LOW-HYDROGEN ELECTRODES

On the practical application of non-basic electrodes it appears that their hydrogen content causes no difficulties at all in a great number of cases when normal unalloyed steel has to be welded. Low-hydrogen electrodes compare favorably, however, as soon as circumstances arise in which it is difficult for the hydrogen to escape from the metal, e.g., if the steel contains large quantities of sulfur or if the material is relatively thick (although in the latter case preheating the metal may sometimes prevent dangerously high hydrogen concentrations during the welding process when using non-basic electrodes).

Care should be taken that low-hydrogen electrodes do not lose their good qualities by absorption of water vapor from the atmosphere by inadequate storage. Zoethout (8) tried out three simple methods to guarantee a sufficiently dry atmosphere in the storage room for low-hydrogen electrodes:

(1) Keeping the temperature in the storage room permanently at least 10° C higher than the outdoor temperature.

(2) Placing containers filled with hygroscopic substances in the storage room.

(3) Continuously conveying dried and heated air into the storage place.

In practice each of these methods proved to be sufficient.

When welding in the open air, a storage place that comes up to one of the three above-mentioned requirements will in most cases not be available. The following procedure was therefore adopted when a large open-air project had to be carried out in the Netherlands. The basic electrodes were delivered in boxes by the Philips welding rod factory to the unheated storeroom; these boxes were at once placed in tins which were sealed with gummed tape. Packed in this way the electrodes could be stored without any deterioration in quality. Naturally, after a box was opened, some

of the electrodes were in contact with the open air for several hours. However, the moisture absorbed by the welding rods during this period was never sufficient, not even when there was a thick fog, for poor hydrogen characteristics to develop during the welding process.

SUMMARY

Nowadays coated welding rods are almost exclusively used for electric arc welding. The coating should transmit little oxygen (and nitrogen) to the metal during the welding process, since otherwise bad quality welds are obtained. Suppression of the oxygen transmission causes absorption of large quantities of hydrogen if nonbasic welding rods are used. In unfavorable circumstances this may give rise to porosity and cracking of the weld. In order to decrease the hydrogen content, the welding rod should contain as little water as possible. Basic or low-hydrogen electrodes were developed to meet this requirement. For these electrodes to keep their favorable properties, they have to be stored in a special way.

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THE ORIGIN OF ENGINEERING DUTY ONLY

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THE AUTHOR

After graduating from Cornell in 1917 as a Civil Engineer, came to the Navy Department for duty in the Bureau of Construction and Repair, Aviation Section, under then LT. J. C. Hunsaker, CC, USN. Later entered the Civil Engineering Corps after examination.

Sometime shortly after 1921, there was a move on foot in the Navy to amalgamate certain staff corps with the Line of the Navy.

The author was assigned to conduct a referendum among the officers, and, as he recalls it, only two (2) gave any open leaning toward amalgamation, and these had certain stipulations which negated their value.

In regard to this article the author states "I conducted much independent research and naturally turned to the amalgamation of the old Steam Engineering Corps with the Line of the Navy in 1899.

"In investigating this matter I talked with Admiral Dyson who was then in the Bureau of Steam Engineering, and he aided me considerably in further research. This research led into various reports of the chiefs of the Bureau of Steam Engineering; the Congressional Hearings at the time of the proposed amalgamation; at hearings on the Act of August 29, 1916, which established EDO; and various Navy Department histories.

"In all, several hundred pages of pertinent matter were collected, and the enclosed article has been boiled from that research.

"The difficulties under which the early engineers worked deserve to be recorded, because there is a lesson to be learned which influences the resulting development of personnel and materiel."

No study of the Bureau of Steam Engineering and the Steam Engineering Corps could ever be complete without considering the influence of Rear Admiral George W. Melville, USN, Chief of Bureau from 1887 to 1902.

His immediate predecessors were: 1881-2, W. H. Shock; 1883, W. H. H. Smith; and C. H. Loring in 1884-6.

Melville was born in 1841 and died in 1912. A graduate of Brooklyn Polytechnic Institute, he entered the Navy

in 1861, served through the Civil War, and remained in the Navy. In 1879 he became identified with Arctic exploration.

He is known as a very modest man, rather two-fisted when it came to expressing himself, and, as he struggled in his job as Engineer-in-Chief for fifteen years, it is highly probable that his ability to blow off steam and his tenacity saved him from a breakdown. In spite of his continual pleas for additional personnel, no one paid the slightest attention to him until Theodore Roosevelt became Assistant Secretary of the Navy in 1898.

But, let us go back and set the stage. The first successful steamboat for commerce was Robert Fulton's *Clermont*, which in August 1807 journeyed 150 miles from New York to Albany in 32 hours.

The first steam man-of-war, the USS *Fulton*, had a trial trip in 1815. It carried 26 guns, made over 6 knots, and was destroyed by fire a few years later.

Steam propulsion became more feasible for battleships through Ericsson's successful application of the screw propeller in 1837, which eliminated the exposed side paddle wheels. In 1843, the USS *Princeton* became the first American warship to be screw-propelled. But, even at the outbreak of the Civil War, all U. S. Naval vessels had auxiliary sails. The *Princeton* was the first vessel to use anthracite coal and, therefore, the dense volumes of black smoke were eliminated and secrecy of movement preserved.

The battle between the *Monitor* and the *Merrimac* was the first battle between steam-propelled warships.

The first crossing of the Atlantic by a steam vessel occurred in 1837. In 1855 all transatlantic ships still had side-wheel paddles.

When the Steam Engineer Corps of the U. S. Navy was formed, like all new organizations, it had to struggle against terrific odds. It never overcame the prejudice against it. It also lacked sufficient officers to successfully perform its mission. This mission would have been to provide the Navy with the best propulsive engineering machinery and the best qualified personnel for its operation.

Much of the opposition came from the commanding officers of vessels who resented the change from sails to steam and confirmed the old adage "You can't teach old dogs new tricks," whether they be sea dogs or otherwise. They objected very vociferously to the coal dust which blanketed the ship after coaling operations; the soiled uniforms of the black gang; and also to the soot-soiled sails. They stubbornly ignored the additional fighting and maneuvering power obtained through steam propulsion as well as other advantages.

After the Civil War, American naval construction lagged for a number of reasons. Senior Naval officers, accustomed to immaculate sailing vessels, stubbornly resisted the introduction of steam. Statesmen were confused because the Navy was not unanimous on what it wanted. Some officers correctly pointed out that one well-directed shot from a heavy gun could paralyze a steamer and render her immobile in the water.

One additional excuse can be offered for the attitude of Congress towards the Navy. After the Civil War, changes in naval construction followed each other with such bewildering rapidity that naval constructors and line officers held the most divergent opinions as to the types of ships worth building, the amount of sail power to be retained, the kind of engines, the use of steel or iron, the amount of armor plate, etc. Naturally, Congress was unwilling to appropriate money in the face of such a confusion of ideas.

By 1881, the Navy was at its lowest point of strength relative to foreign

navies since 1815: Twenty-five tugs and 115 other vessels with only a few in condition to make a cruise and not a single ship fit for war. A review put on for the President included the best vessels of the time and included the 82-year-old *Constitution.* American captains were ashamed to take their ships to European waters. After strained relations arose with Great Britain from the Alabama claims; with Spain over the Virginia affair in 1873; and when France moved into the Isthmus of Panama in 1880 without regard for the Monroe Doctrine, it began to dawn on the public that European nations could ignore our protests only when backed by a few rotten hulls.

As a result, President Garfield appointed an Advisory Board which recommended thirty-eight cruisers and thirty other vessels. Eighteen of the cruisers were to be of steel and twenty of wood. The minority members of this Board included three Naval constructors and the Engineer-in-Chief. They opposed the use of steel and recommended iron because we had no plants capable of producing the required steel. It should be noted that the new market created new plants to produce the steel and as a result, the Navy got great credit for aiding in the establishment of this new industry.

Congress was willing to do something, but not quite that much. It authorized only seven vessels and then failed to appropriate for them. Later, there were appropriations and additional vessels authorized. In the meantime, however, the Steam Engineer Corps was not allowed any increase in officer personnel to man the new vessels.

Thus, we come to the period of 1887 when the new Chief of Bureau moved in to remain Chief for 15 years and bring the Navy definitely out of the period of sails and wood and into the period of steam and steel. What manner of man was Melville?

In the summer of 1879, LCDR G. W. DeLong headed an Arctic exploration group leaving San Francisco in the steamer *Jeannette.* The government cooperated with James Gordon Bennett of the *New York Herald* and the object was to try to reach the North Pole by following a branch of the Japanese current. Ice flows were soon encountered. By September the vessel was wedged in and frozen solidly, in danger of being crushed. Once she would have foundered but for the skill of Chief Engineer Melville. Summer did not bring release and another year dragged by in the Arctic prison. Finally on June 12, 1881, the *Jeannette* was crushed and sunk by the ice. Her crew, stranded on the flows, was left in mid-ocean with 3 boats and scanty provisions and clothing. The only chance of escape was to reach the settlements on the Lena Delta, five hundred miles away.

Melville succeeded in reaching these settlements after fearful suffering. One other boat was never heard of again and the third cutter under DeLong almost made it. Later a message reached the settlement and Melville went out and tried to find DeLong and his men. He finally located them the following spring. They had died soon after the message had arrived.

There is the example of a man whose iron will kept him and his men alive. Here is a man who was destined to be Chief of Bureau of Steam Engineering for fifteen years; who fought under the handicap of inadequate support from the Secretary's office; who had to operate ships with an inadequate number of officers; and who called attention to his personnel situation in vain year after year.

To read his annual reports, one wonders why he didn't resign in protest in order to publicize the lack of engineer officers. A less determined individual would have been a candidate for psychiatrists due to the constant frustration and opposition that he experienced.

Melville's outstanding services were of great importance to the U. S. Navy. During a period when a new and more modern Navy was being constructed, he was responsible for the design and machinery of more than one hundred and twenty naval ships. He introduced the triple screw; was also responsible for the change from horizontal boilers to the more efficient vertical type and the introduction of the water tube type boiler. He foresaw the future importance of oil as a fuel and carried out some of the first tests ever made to determine the relative values of various types of oil.

In order to demonstrate conclusively the tenacity of Melville's character, and what the Engineering Duty Only officer of today owes to him, it will be necessary to quote excerpts from his annual reports to the Secretary of the Navy. These annual reports were very lengthy concerning personnel, but no repetitious material has been quoted in this article, merely the different illustrations provided by Melville in proving his contentions.

Before the Amalgamation Act of 1899, the relative rank provision determined an officer's pay in the Staff Corps. Staff Officers might be divided into two or three grades as far as their profession was concerned, such as: Assistant Engineer, or Assistant Naval Constructor, etc., with the rank of Lieutenant, etc.

When promoted from one relative rank to another, an officer still retained his designation as Assistant Engineer, etc. The change from Assistant Engineer to Engineer generally came at a time when no other promotion was involved.

Staff uniforms consisted of stripes on the sleeves with some color between the stripes to distinguish the different staff corps in lieu of the present corps devices. For instance, the old Steam Engineer Corps had red between the stripes; Professors of Mathematics, olive green; Naval Constructors, purple; Civil Engineers, light blue; Paymasters, white; Doctors, maroon; Dentists, orange; and Chaplains, black.

These color schemes are all but forgotten today, but there must have been some interesting anecdotes prevalent 50 years ago.

When the Steam Engineer Corps was organized, its sponsors had to struggle against intense prejudice because old and most influential Naval Officers were bitterly opposed to the invasion of steam into a field which they regarded as their own. Mr. Paulding, Secretary of the Navy, was credited with holding up the introduction of steam into the Navy for a number of years. His diary tells of attempts to introduce steam and stated that he "never would consent to see our grand old ships supplanted by these new and ugly steam monsters." He complained of being steamed to death. (The monsters in question were the *Mississippi* and the *Missouri*. The engineers thought them beautiful ships and they were right because there is a beauty in utility too.)

The prejudice against the Steam Engineer Corps slipped over into the field of promotion, rank and general equality. During the Civil War, line officers had been promoted, whereas the sea-going engineers were not given the same promotions. This caused widespread discontent, which was increased when an order was issued to deprive them of the assimilated rank given them during the Civil War as a reward for a job that was efficiently performed.

As was only natural, Congress soon heard of the discontent of the members of the Corps and a bill was introduced in the 41st Congress by the Honorable A. F. Stevens, of New Hampshire.

Mr. Stevens explained the difficulties, and after exhaustive hearings the bill was passed in January 1871. This bill set out to define rank in the Navy similar to the definitions of rank in the

Army. The bill stated that there would be a definite number of medical directors with the rank of Captain, chief engineers with the rank of Commander, etc., and it spelled out the various ranks in a way that made it mandatory for the Steam Engineer Corps officers not to be discriminated against.

The bill was attached to the Naval Appropriations Bill and passed the House in the exact form desired by the Engineers. It took away from the Navy Department any flexibility in the matter of promotions. Someone with influence got the ear of a powerful Senator and had the rank of the staff qualified by the word "relative to." This amendment was adopted in conference and, although unfavorable to the Staff Corps, was accepted in view of other benefits which were conferred by the bill. The bill became a law March 3, 1871.

For several decades there was friction between the line and the staff due to this relative rank insertion with the net overall effects of decreased efficiency in the Navy. Presumably, the influences which put across this relative rank idea were pleased with the day's work but a little generous fair play on their part would have made the Navy a better and more efficient force due to contentment and morale of all its personnel, including the staff officers.

Certainly no large business institution of even that day would have permitted a sales force to relegate the manufacturing force to an inferior position, or permit discrimination whereby one group would have a supercaste over other groups.

Congress intended to confer actual rank on the staff officers and that can be clearly determined from the hearings that were held beforehand. But later, a peculiar definition was applied to the term "relative." Here is what the Senate thought "relative" meant. Senator Conklin: "With the permission of the Senator, I wish to suggest a point to him. He says that he understands 'relative rank of' to be the same in effect with the words 'to rank with.' I wish he would tell us what would be the force of this if the word 'relative' were omitted; in other words, what 'relative' means. I understand it when you say a commodore in the Navy shall have the relative rank of a major general in the Army, there being two services separate and distinct. I know what that means. But when you speak of relative rank in one and the same service, what is the definition of the word 'relative' there? How does it enlarge or restrict it?" Mr. Cragin: "I will have to go back a little to answer that question. In the Navy, there are four or five different corps. There is the Line Corps, which, in the English service, is called the Military Branch. Then there are the Medical Corps, the Pay Corps, the Engineer Corps, and the Constructors. They have just as positive rank in their corps as the line have in theirs by law now, and the only reason why they need any relative rank at all in the Line Corps is to define their position with the Line Officers: to give them social equality, and official equality in everything except what pertains to actual command."

Mr. Stevens stated in the House, "I desire to say, in regard to that portion of the report regulating the official relations of the several corps in the Navy, that it is the bill which passed this House by a very large majority. Although the committee of conference were not able to embody in terms that bill in this report, yet I think I may safely say that very much has been gained to the Navy, and very much to the Staff Corps of the Navy, by the provisions of this bill as amended. Substantially there were but two points of difference between the committees of the two Houses upon this question. The first was in regard to whether the Staff Corps of the Navy should have actual rank, in conformity to the law regulating the Staff Corps of the Army; or

whether it should be an assimilated, imperfect, inchoate rank; or a fixed, positive, actual rank, and I think that it was the opinion of the committee that this bill conferred upon the Staff of the Navy the same rank and official position that are enjoyed by the Staff Corps of the Army. At least, the same corresponding position. There was some sensitiveness in regard to terms; concession became necessary. I wish to say, Mr. Speaker, that while the term 'relative' is used in conferring position and rank upon the Staff Corps, my belief is that a fair and liberal interpretation of the language of the bill by the Navy Department, and those charged with its execution, will place the Staff Corps of the Navy in the same position in relation to that organization that is conferred upon the Staff Corps of the Army. That was the purpose of this bill as it originally passed the House, and a just interpretation will accomplish it."

Thus it is clear what Congress intended, irrespective of how the Navy Department applied the term. So much for relative rank.

Now let us examine the personnel situation prior to Melville.

In 1881 the Engineer in Chief, W. H. Shock, stated that there were 27 vacancies in the grade of Assistant Engineer, but presumably they would be filled by graduates of the Naval Academy.

In 1882 he pointed out that the Act of Congress in 1874 provided that only twenty-five cadet engineers should be appointed annually. The Board of Visitors was not too well impressed with the training that the Cadet Engineers received, and the Chief recommended that the cadets be permitted to elect the branch of service they preferred and to pursue special courses through the Academy.

He also pointed out that the act of August 1882 allowed only sixty passed and forty assistant engineers with the same number of steam vessels in commission, there would be less than three watch engineers to each ship in commission with no allowance for reliefs for any cause. This reduced, what with shore duty, the number assigned to each vessel. Generally, only one passed, or one assistant engineer, could be assigned to a ship.

He stated that no merchant steamer was allowed only one assistant engineer. He also predicted a great increase in costs from repairs to boilers and machinery, as a result of this shortage of officers. They had tried to use mechanics or machinists in lieu of engineers, and after an eleven-year trial, it was evident that maintenance costs were increasing beyond reason.

In 1883, the new Engineer in Chief W. H. H. Smith, reiterated his predecessor's pleas and pointed out that underwriters would refuse to insure any merchant steamer with the same lack of engineering personnel as in the Navy. Further, that the owners of such vessels would be liable to criminal prosecution.

The cadet-engineer system at Annapolis, first tried by our Navy, was speedily followed by England and others which established special technical schools for training of the engineer officers. Then our Navy abandoned the system and moved back twenty years, he stated.

In 1884, a new Chief of Bureau, Charles H. Loring, again called attention to the inadequate numbers of engineers. In order to keep vessels adequately staffed, he found it necessary to deny engineer officers their proper periods of shore duty.

In 1887, Melville became Chief of Bureau. Melville was well acquainted with the situation which he inherited when he took over. He deplored the abolition of the former course of instruction for Cadet Engineers, and he

pointed out that the Naval Academy Superintendent recommended that cadets be divided at the end of the third year. Thereafter, they would study only the profession of the corps for which selected. Melville recommended that the separation take place at the end of the second year.

He also took a strong stand concerning "relative rank." He pointed out that, under existing law, his officers do not rank with the class of line officers with whom they are graduated, but after the class with which they entered the Academy, and which was subsequently graduated.

Melville, pointing out annoying discrimination on the part of some Commanding Officers, stated, "I would call attention to the various ways in which Commanding Officers interpret the duties of engineers on board ship. Some very rightly leave the arrangement of watches and the distribution of duties to the Chief Engineer, holding the latter strictly responsible for the faithful performance of the duties of his subordinates and for the efficient working of the machinery. Many Commanding Officers, however, arrange these details to suit themselves, often requiring the engineers to stand regular watches in the engine room at all times, day and night, whether there is anything to demand their attention or not. Standing a watch, as does the Officer of the Deck, with duties pertaining to military routine to perform, is one thing; and standing watch as engineers are frequently required to do, over a mass of cold cast iron, is quite another. The latter is neither inspiriting nor healthful to the victim. The arrangement of these details should be left to the Department, commanding officers being allowed to change them only in case of emergency. The number of engineers sent to each ship should be arranged according to the importance and complication of the machinery, and nobody is more competent to judge this than the Bureau of Steam Engineering. Where the number of engineers is sufficient, they should be required to stand watch, but when under steam on the main engines only. No engineer should be required to stand a watch except when there are duties to perform which demand an engineer's constant attention. The idea that an officer is not doing his full share of duty when he is not as uncomfortable as it is possible to make him is too prevalent in the service. It will be found that engineers will take more interest in their duties and perform them much more satisfactorily when they are not required to perform imaginary duties for which no necessity exists."

He then went on to give a complete picture of other difficulties in administering the engineer's force on board ship as follows:

"The firemen are kept on deck by the hour and exercised in the manipulation of the spars and sails, while the work below is neglected. Not very long ago, the chief engineer complained that he was unable to do the necessary overhauling and repairs, as he was not allowed the use of his men. The reply of the commanding officer was that the presence of the men at the drills could not be dispensed with, and that if repairs to the engines were necessary they could be done at night. The result of such action is inefficiency of the motive power and unduly rapid deterioration of the boilers and machinery. The average life of our boilers is less than it should be, and many of our engines, although originally economical, have become wasteful of fuel simply from want of attention, while the labor which should be used on them is diverted into other channels. This must all be changed, and changed quickly, if our vessels are to be kept in effective condition. The Department enlists men for the engineer's force for the purpose of manipulating and taking care of the machinery, and they should not be employed for other purposes while this

work remains undone. None of these men should be employed in any work other than that for which they were intended, without the previous statement of the engineer officer in charge that his department is in such a state that their services can be spared, this statement to be recorded in the steam log-book. The coal-heavers should be considered as a permanent part of the engineer's force, as was intended when the rating of Coal-Heaver was established.

"The Blacksmiths, who were recently taken away from the engineer's force and put under charge of the Executive Officer, should be returned, as nine-tenths of all the blacksmith's work on board ship is in connection with the engineer's work, and the blacksmith should be available to do this work when necessary."

Contained in the above excerpts is probably as good a definition of a martinet as could ever be obtained. He might be defined as "one who believes that an officer is not doing his full duty when he is not as uncomfortable as it is possible to make him."

In 1888, Melville stated that with the new vessels now building, the shortage of engineers was becoming more acute. He pointed out that there were 725 line officers vs. 220 engineers and these included cadets who had recently been commissioned. The above percentage was 30%, whereas in the British Navy there were 46% as many engineers as line officers.

He also pointed out in 1888, that his corps was being reduced to a limit of 170, whereas the similar corps in the British Navy was being increased to a limit of 750. When those limits were reached the percentage would be 23.5% in his corps as against 49% for the British Navy.

He further declared that the British Navy was supplemented by an excellent force of "engine-room artificers," superior to the USN force of machinists. And that for the past 20 years, there was a steady decrease in the number of engineers although naval machinery was becoming increasingly complicated.

He recommended an increase to at least 300 engineers. Not getting his cadet engineers adequately trained with a definite engineering course of instruction, he recommened that a number of appointments be annually given to mechanical engineer graduates of technical schools such as Cornell, Stevens, etc.

He further pointed out in this extensive 1888 report, that he was losing many of the young officers and the principal causes therefor were "the steerage." He explained, "This is a part of the quarters on board ship which had its origin in the necessity for an apartment separate from the quarters of other officers, which would serve as a sort of nursery for the midshipmen of tender years who obtained their first naval training on board ship. Such a necessity no longer exists, for officers now first enter upon their shipboard duties at an age when they should be treated as men and not boys. Moreover, as promotion goes and under existing regulations, many of them remain "steerage officers" until middle age. Many ensigns, by being assigned to duty as "watch and division officers," happily escape the trials of the steerage after a few years, but the assistant engineers are obliged to occupy these quarters until promoted. There are some of these officers who have spent eight years' sea service in the steerage, and not likely to soon escape from it. Some of the steerage officers are from thirty to thirty-five years of age. That men of this age should be huddled together, like school boys, in a common dormitory, is absurd, the only excuse for it being the traditions of the service."

In 1889 he reiterated previous pleas and stated that a British Board of Ad-

mirals on Naval Maneuvers for 1888 recommended another increase of engineer officers, and that it did not seem wise to him to wait until war came to profit by the lesson.

He pointed out that there was a great difference between the machinery of twenty or thirty years before and that the "few ships in our Navy that were provided with forced draft go crawling around the world on an 'allowance' of coal, burned under natural draft, just as they did a generation since." He pointed out that forced draft was almost unknown in the merchant service and that the kind of men needed to operate it could not be obtained ready-made for the Navy.

He called attention to the imperfect method adopted in assigning men to the engineer's force on board ship, and in fixing the ratings of such men. The last board on ratings did not include an engineer officer on the board although the engineer force in the new ships comprised from 30% to 50% of the ships complement. He disapproved of the board not allowing ships a coppersmith. This resulted in costly repairs in foreign ports. The reason given by the board for not allowing a coppersmith was "a plumber was allowed to the ship and he could do all the pipe fitting." Melville stated that "a more inadequate reason can hardly be conceived. As well might it be said that sail-makers' mates should not be allowed on vessels where there was a ship's tailor."

He further pointed out that addition of machinery had eliminated much of the drudgery formerly performed by the crew but in spite of this, the engineer force was not being increased to take care of the additional machinery.

In 1890 he recorded that matters were in worse condition than they were a year before, and he repeated his former recommendations with emphasis. Here he brought up a new argument, as follows:

"There is still another and very important point that is generally overlooked when considering the Engineer Corps of the Navy, and that is that they are a part of the military organization and second to none in importance. In the naval battle of the future, the engineer staff will have a difficult and important part to perform and if there is failure in the engine room, no amount of skill and bravery on the bridge may suffice to avert disaster. Celerity of movement has decided many a naval battle and will decide many more, and the celerity of movement of a modern ship depends directly on the skill of her engineer officers."

He again called attention to the desirability of abolishing the steerage and pointed out that some line officers escaped with but one cruise in the steerage but not the assistant engineers.

As an argument for more men in the Engineer Corps, he quoted an article by Admiral Luce on "Naval Training" wherein Luce stated that the services of but two men are necessary on deck to take a modern ship to sea; "one at the lead and one at the steam-steering wheel."

In 1891, he called attention to a collision which occurred between two naval vessels which was directly traceable to a lack of sufficient engineer officers. He continued: "It cannot, therefore, be a matter of surprise that engineer officers are breaking down from overwork or resigning to escape it. Indeed it has been sometimes claimed that, by reason of this nervous strain, engineer officers age more rapidly than others, and should be retired earlier in consequence. Besides this first and most important result of paucity of numbers, is another almost as great—the necessity of abandoning other work of great value to the service and the country at large."

Engineer officers were detailed as instructors in technical schools under an 1879 Act of Congress. Their work was

highly commended by college presidents who opposed their withdrawals due to the reduced numbers in the corps. The result "has been that a number of schools have been unable to maintain a mechanical course."

Just about the time we begin to wonder whether anyone in the Navy Department ever read these annual reports, Melville reports in 1891 that the Secretary of the Navy and the Chief of the Bureau of Navigation both recommended an increase in the Engineer Corps and that a bill had been introduced in Congress which provided for technical school graduates being commissioned in the Engineer Corps.

His comments on the abolition of steerage are more illuminating in his report of 1891: "It is a relic of barbarism, and is as much out of place on a modern ship as would be a slow match for the guns; it is productive of the greatest discontent, and is an injustice to officers who are charged with important and responsible duties. Where the number of engineer officers on board ship is so small as at present, it is inevitable that they should be up and around a great part of the night, and to preserve their health, they should have a room where they may rest when off duty in the daytime. I can conçeive no reason why all commissioned officers should not be members of the wardroom mess, and I earnestly recommend that the Department take such action as will secure this most desirable end.

"This Bureau has always maintained that the best designer of marine machinery is the man who has learned by practical experience at sea, and in charge of it, what to strive for and what to avoid. He knows that efficiency does not follow as a matter of course from complexity, but that simplicity, accessibility for inspection, facility in overhauling, and the smallest possible number of parts are the prime requisites. Many designs look very attractive on paper to the disastrously ingenious draftsman who has never seen them utterly fail to work at sea, but the trained engineer, who has lost hours of important time in repairing such puzzles, learns to avoid them almost by intuition."

He pointed out that the newspapers were giving great space to descriptions of new naval vessels, but little was said about the people who made the movement of the ship possible because they are out of sight and "only attract notice when an accident occurs or speed cannot be attained."

He again pleaded for adequate provision for a supply of thoroughly trained mechanics and firemen. He complained of the undue prominence which was given to the so-called military drills on board ship.

He recognized the need for thorough training for every man aboard ship in order to obtain maximum efficiency. The final strength or efficiency of any organization could only be that of the weakest portion or the most poorly trained division.

Important work on machinery had to be postponed or omitted because the firemen and coal heavers were sent on deck to take part in drills even though in time of war these men would be required in the engine and fire rooms. He continues: "I do not for a moment suppose that this has been done with any desire to decrease the efficiency of the machinery, but from thoughtlessness and a desire to secure the highest efficiency in military exercises and the exaggerated importance assigned to them. It should not be forgotten that if the men of the engineer's force are so constantly drilled in small arms, great guns, landing parties, etc., that the machinery is neglected or slighted, the vessel soon becomes what is called a 'lame duck,' and all the guns and gunnery and infantry tactics in the world cannot make her either formidable or efficient. It should be also noted here that nearly

every steam log received speaks of the insufficient number of firemen and their inefficiency; they are willing enough but have not had the necessary training. I believe, therefore, that for the present all efforts should be devoted to making them efficient as firemen and leave the matter of their proficiency in other things to future consideration."

He pointed out in 1892 that since his last report, twelve officers had been lost to the corps for various reasons. There were only three replacements for the twelve experienced men lost. He deplored the crippling act of 1882 which reduced the corps' strength and pointed out that thirty-nine young officers educated at great expense had resigned from the corps as a result.

He claimed that the situation had become so utterly inadequate that it was a matter of cruelty to assign officers to sea duty where their hours of incessant and laborious toil performed under great mental strain and the weight of responsibility are greater and more exhausting than those of the laborer on the streets or in the building trades.

His picture of what went on in the larger ships was illuminating: "On our most powerful ships—those of from 5,000 to 10,000 horsepower— the usual complement now is one chief engineer and three assistants, the latter being obliged to stand watch in three watches at sea and often in port; a duty so exhausting that no officer can long perform it efficiently, for he never has a whole night's rest, and when on duty has to withstand a constant merciless assault upon his physical and mental powers. His post of duty is one of intense heat and villainous atmosphere; to get from one part of his station to another, which he must do very frequently, he must climb up and down narrow ladders, crawl through air locks, explore coal bunkers, etc., all the time in a state of mental anxiety on acconut of the innumerable casualties that are constantly occurring, and for the prompt remedying of which he is strictly accountable; in one water-tight compartment some boiler tubes are leaking and the men are in a panic; in another, a hundred feet or more away, a feed pump is refusing to work or a thrust bearing is hot, and while hurrying from one scene of danger to another the engineer is liable to receive tidings of trouble in some remote coal pocket, or even be summoned to appear on deck, where he must calmly answer questions regarding the amount of smoke escaping from the smoke pipes or the necessity for hoisting ashes, wholly unmindful of the disasters which he knows are impending below. So it goes, watch after watch and day after day, until in the course of a week or two the engineer is a nervous wreck, fit for nothing but the hospital; and all because the lack of numbers imposes upon him the work of at least two men."

He cited the case of the *Ranger,* needed to protect the seal fisheries in the Bering Sea. The engineer officer of the *Ranger* had an accident, was hospitalized, and the vessel was delayed twenty-nine days due to no relief. This resulted in a Court of Inquiry and Melville stated: "The whole miserable affair from beginning to end is directly chargeable to the insufficiency of numbers in the Engineer Corps, which allowed but one engineer officer to be detailed for this vessel."

Melville pointed out that the only opposition to the bill thus far "has come from some of the officers of the Navy who seem to view with jealous distrust the growing importance of the Engineering Branch of the service and see in it an imaginary menace to the supremacy of the positions which they have inherited from naval conditions now obsolete. The plain fact is that the era of the sailing frigate with lofty spars and snowy canvas has forever passed away, and with the passing of the frigate must occur also the disap-

pearance of much of the picturesque personnel which served its purpose in its own time, but which is now out of place on the sea except in its romances. Naval gentlemen who resent the intrusion of the steam engine and its attendants are doubtless sincere in their convictions, and really believe that the *Constitution* is the proper type of fighting ship and that the *New York* is not, but they draw upon the traditions of the past for their propositions and overlook the living facts of the present."

To elaborate further on "relative rank" he stated that those who are commissioned in the line of the Marine Corps are immediately clothed with the rank and title of their grade and receive the honor and dignity of position to which such official status entitles them. On the other hand, those who found themselves in the Engineer Corps, perhaps against their own wishes in the matter, are confined to mere "relative rank," which is regarded in the service as no rank at all, are occasionally taunted in the public newspapers by their classmates with being "civil officers," "non-combatants," etc.; are discriminated against on board ship in the matter of quarters, and in other ways are occasionally humiliated and made to believe that they have been accorded a status inferior to that of their classmates.

He pointed out that the Senate Committee reported favorably a bill to increase the efficiency of the Engineer Corps, by assigning definite rank to them.

He complained of the treatment of the enlisted man in the engineering divisions stating that "if one of them crawled out of the hellhole where he was on duty to get a breath of fresh air, he might be promptly driven below again or even punished for appearing on deck 'out of uniform,' while the discovery of a speck of dirt anywhere on deck subjects any member of the engineer's force who may have the rashness to be above the fireroom gratings to abuse from the boatswain's mates and probable punishment at the mast."

He further stated, "That the decks of a man-of-war should be of spotless purity is a tradition handed down from the days of wooden ships and barefooted crews, and is so impossible a condition in these days of coal and iron and steel, that it seems a little intelligent consideration would lead to its abandonment."

For the Commanding Officer of any vessel who permitted such things to go on, he had a paragraph which he probably hoped would be read: "All these unhappy details are different on different ships, but the general results are the same. The useful and self-respecting man, when he finds himself so unfortunately circumstanced, will in sheer self-defense leave the service forever; another man will accept the situation and become a chronic offender against the Navy Regulations because he finds that he is treated as one anyway."

Again, in his 1893 report, he complains of the insufficiency of the Engineers Corps. He reiterates so much and points out that many of the young officers who are resigning to accept better positions in civil life, would have preferred to remain in the Navy if they could have seen any chance of advancement. He again requested that all commissioned officers be made ward-room officers and steerage be abolished. He pointed out that as far as slurring remarks directed at the Engineers as being "non-combatants," the recent loss of the "H.M.S. *Victoria*," which vessel was rammed by another vessel and lost under conditions similar to battle proved otherwise since the whole engine room staff on watch perished to a man.

He answered the contention that the granting of authority to engineers to "command" in their own departments will lessen the authority of the com-

manding officer of a ship by stating that it was as absurd as it was childish. He pointed out that Marine Officers aboard ship have always exercised command over their men and nobody would argue that the commanding officer's authority was lessened thereby. Also, the line officers exercise such command in their divisions, but there was no complaint there either.

He then complained of drilling firemen and coal passers in duty which they would never have to perform in action, and requested that if they must be drilled, that there be some consideration about it. First, that their primary duty aboard a ship be not made secondary to drills; and, second, that they should not be made to drill when steaming in the tropics which is often being done.

He then gave a countersuggestion, viz., "If it be deemed necessary to drill the firemen at the guns, I would suggest that when such drills are in progress, a division from the deck be sent below for instruction and work, so that when occasion requires it, the fire-room force might receive a valuable auxiliary aid from the deck."

In 1895, he again called attention to the shortage of engineer officers and in 1896, he pointed out that the engineer officers were passing rapidly to the retired list due to the physical strain to which they were subjected through the shortage of numbers. He pointed out that to sacrifice the engine room was merely to invite disaster to the whole and no amount of skill on deck would compensate for the lack below.

In 1897, various arguments and requests are repeated.

In 1898, there was a marked change in the tenor of his report and he stated: "In each of my annual reports for the past ten years, it has been my duty, and a sad one, to call attention to the urgent need of a reorganization of the personnel of the Engineer Corps. In this respect, for the first time, I can say with great pleasure that a measure is pending in Congress, approved by the Department, which, if passed and administered with a desire to make it a success, will not only satisfy the recommendations I have made to the Department each year, but will go much further as affecting the whole service, whose homogeneity and efficiency will be immensely increased."

The words "if passed and administered with a desire to make it a success" became very important.

What happened was this. Theodore Roosevelt became Assistant Secretary of the Navy and he was not a man to permit an unsatisfactory condition to run on indefinitely. Hearings were held in April 1898 before the Committee on Naval Affairs and Mr. Roosevelt stated that upon coming into the Department, he found a great deal of friction between the line officers and the engineers, and at first, to him, it was absolutely incomprehensible. There were a number of bills introduced by Members of Congress and others. Finally, the Secretary appointed a Board with the Assistant Secretary as Chairman.

Mr. Roosevelt was accepted as an impartial moderator, and the principal causes of friction, as he recorded them, were in his own words, "They arose from the introduction of the entirely new motive power of steam into the Navy. The old line officers were exclusively trained to sail a ship. They could handle the sails as well as they could command men. The steam engine was something new, and they looked at it with extreme distrust. It is not necessary to remind an officer of the Civil War how Farragut felt toward ironclads. The line officers have taken the view that the engineer was nothing whatever but an engine driver and ought not to have any title or rank, and the line officer would like to abolish him altogether.

The engineer officer has taken the view that the engineer was a limited sphere of business, and only a limited sphere, and that, really, the important man is the engineer. I could get an opinion from the best men in the service in one corps disparaging the corps to which they did not belong, and if you took them all, you would have to legislate on the entire Navy."

Mr. Roosevelt pointed out that if the Board were interrogated, it would be determined that neither side was fully satisfied with the solution but they were for the compromise. He pointed out what the engineers have long contended, and he thought quite rightly, that electricity should go under them as much as steam. His view was that the department, by detail, should reverse the policy that had been for some time obtained, of having every man in turn do every duty; the fact that he has performed the duty being considered a reason why he should never perform it again; and on the contrary, specialize after eight or ten years' service.

He stated that the bill provided for proper specialization by detail. He was opposed to having any hard and fast law by which you would have all the steam engineering in one corps, electrical in another and so on. The Chairman pointed out that in these distinct lines of profession, specialties were prevalent in the business world today. T. R.'s solution was that every competent line officer on board ship would be an engineer; to which the Chairman answered, "And yet, with the highest regard that I entertain for those gentlemen, there are some of the most accomplished officers in our Navy who, if they should be in charge of the engines, and if the handling of a great ship like the *New York* depended on them, I would not go out of port with them, and you would not." To which T. R. agreed.

T. R. said that the line regarded it as a grievance that the engineers should wish to have their rank and title. Further, "that the general run of the line contend that the engineer was not needed on shipboard at all; that what was needed was the machinist; that the skilled machinist could do all the engine driving that the Annapolis-graduated engineer or the college-trained engineer did, and that the line officer himself could oversee the work so far as was necessary, and that the Navy would be better off with machinists on board ships in lieu of engineer officers."

He further stated that the line officers objected to the engineer being made a line officer because they felt it would drive the line officer out of the ship. He stated that the broader-minded line officers felt that any part of discontent in the engineer ranks could be removed without impairing the efficiency of the service.

Teddy pointed out that under the present conditions there was a corps championing each side, but under amalgamation, they would all be line officers and it would just be a disagreement between two officers.

One Congressman felt that only one year of study at Annapolis would not provide men equal to the engineers who are being educated at technical schools throughout the country. He wanted to make sure that officers assigned to engineering work be given competent educational training.

Commodore Crowninshield admitted that he strenuously objected to an extensive amalgamation, one which gave titles to the older engineers as he felt that they could not perform the duties of a line officer. The Commodore further claimed that if the older engineer had a line officer's title he would be passing himself off as something he was not, just as the United States Senate would object to the Clerk of the Senate being called a Senator.

The Commodore was asked the question by one of the members, Mr. Day-

ton: "Do you think it is fair that a man who goes through the same course at Annapolis that you did, side by side with you, and who slept with you during that term, that he should be arbitrarily placed in a position below you and that he should not have as good a rank or the same rank as you?"

The Commodore blew up and stated that he did not state anything of the kind; that when he was at Annapolis, there were no engineers there. The Commodore pointed out that a line officer who went from assignment to assignment would not have anything to do with engines for an appreciable period of time and if he went into the engine room, he would not be very well fitted for the job. The Commodore continued, "I think about the average man of common sense—take myself for instance; I take an interest in machinery, and when a thing is explained to me, I understand it; I have inspected engine rooms and all that, but I should feel myself very far from competent to go down and take charge of a lot of machinery. Certain men can do it, but a great many others cannot, in my opinion."

The Chairman pointed out that if engineering duties were thrust at line officers also, they would not have enough seamanship experience by the time they arrived at command rank at sea.

Melville stated he was unqualifiedly in favor of the bill for the reason that he had been pleading with the Committee for an increase in the Engineer Corps, but that he had gotten nowhere; that he thought that this bill would be an improvement. He pointed out that Congress told him that if the line and engineer officers would get together and agree on the bill, Congress would be ready to act, so that he was accepting the bill as a compromise bill. He stated that the great majority of officers composing the engineer corps wanted the bill; he had nothing to lose or gain since he would retire before long.

Melville pointed out that Captain McCormick with whom he had sailed twice, said he had observed no great friction between the line officers and the Engineer Officers of his ship.

"That is because Captain McCormick is a very clever man. He would not let a line officer abuse an engineer officer."

Melville continued, "But I have served in ships, gentlemen, where the captain and other officers encouraged the line officers to abuse the engineer officers."

He pointed out further, in reply to a direct question, "that we have neither the rank nor the title. I have been looked upon as the stepson of the Navy, as it were. I have got tired of being the stepson or the bastard son of the Navy. I was made to understand that I was a thoroughly efficient officer in my own branch of the service, but I was in the service but not of the service."

Melville pointed out that the hundred additional officers that he was asking for would be provided through the operation of the bill. By the amalgamation scheme, something like 350 ensigns and junior lieutenants would be available to be assigned to service in the Engineer Corps, depending upon the exigencies of the service.

Melville stated that when he went before the board, what he wanted was a total of 300 engineer officers and the rank and title of the grade. The vote was seven line officers against him and four engineer officers for him. The bill which was presented to Congress was a compromise bill and under it all officers entering the service were to be engineer officers—in other words, every line officer was to become an engineer officer and thus would be available for detail. In reply to a supposition by a Congressman that Melville wanted rank and title for the power that it confers and not for the mere name, Melville replied,

"You are right; a man in a military organization without a commission is in this position: The commanding officer can put him in irons, can put him on bread and water, can treat him in the harshest kind of manner. A man with a commission but without a title is always apologizing—'I am Mr. Melville, with simply a trade-dollar rank of commodore.' I must apologize to everybody for being on the ship at all.

Melville further testified that all the corps of the Navy were first invited by the Secretary of the Navy to send a representative when the bill was being framed. All declined except the line and the engineer corps.

So the bill was passed and now we may see what happened. Certainly, if all the line officers became engineers, Melville could staff his ships' engineering departments adequately.

However, in his 1899 report, he stated that he approached the subject of personnel with some hesitancy, owing to his inability to see indications of the desired result from the new personnel bill. The spirit of the bill was to greatly increase the number of officers who would give earnest attention to engineering matters and "that it in no way was aimed to augment the forces available for deck or line duty." He asked that no departmental regulations be formulated which would destroy this belief, and that there be an alternation of deck and engine room duty for the present watch officers of the line, in order that there might be no future shortcomings.

In 1900, Melville reports "another year of experience under the provisions of the personnel bill finds the status of steam engineering interests in the Navy even less fully protected, and the number and condition of the force for their control even less satisfactory than when I made my last annual report."

He pointed out that surely enough time had now elapsed since the enactment of the reorganization scheme to make criticism of its effects both proper and important. "To any close observer, it is convincingly evident that either the scheme was a mistake, or that the proper course has not been taken to carry out its intent." He then pointed out that there were available over one hundred less engineer officers than just prior to the personnel act.

Again in 1901, Melville stated: "engineering efficiency in the Navy is rapidly decreasing." He pointed out that the law, as passed, was not being interpreted in accordance with the hearings which preceded its passing.

He pointed out that the following statement made by Assistant Secretary Roosevelt assured the passage of the bill: "Every officer on a modern war vessel has to be a fighting engineer." And that statement had received the widest approval. He pointed out that prior assurance was given that officers who were to be trained in engineering duties were to be given alternation of duty between deck and engine room. It was not specifically stated in the bill because it had been stated that it could be best carried out by departmental order.

Melville pointed out that the boiler plant was the heart of the vessel and any weakness in that department would be followed by a decline everywhere else. He gave as an illustration, the battle of Santiago; the crowning act of that victory was the overtaking of the *Colon* by the *Oregon*. In this chase, a battleship of sixteen knots speed manned by a efficient engine room force, overtook a twenty-knot armored cruiser whose motive power was inefficiently handled, since only about one-half of the boiler power was developed on board the *Colon* that could have been secured by a skilled force of mechanics and firemen directed by a competent complement of engineer officers.

Melville's 1902 report recommended the establishment of a P. G. Engineering

Course at Annapolis, to train junior line officers for engineer duties. The number of young line officers who had especially interested themselves in engineering had been too small.

When Admiral Rae succeeded him, the 1903 report requested that additional line officers be detailed to engineering duty.

In 1904, Admiral Rae became more insistent that more officers be provided for engineering duty. In 1905, he pointed out the deplorable accident on USS *Bennington;* that the older officers were rapidly disappearing from active service; very few officers of the line were taking up engineering, and the situation was becoming alarming.

Rae was opposed to the reestablishment of the Engineer Corps because he thought that frictions were being eliminated; that engineering logically belongs in the line; that it was contrary to military discipline to have the crew under two separate and distinct bodies of officers. In 1907, he again recommended specialization in engineering.

In 1909, Rear Admiral Cone, the new Chief of Engineering, stated that every Engineer in Chief since 1899 seriously advocated special training for a group of officers to replace gradually the retiring engineer corps officers. General Order 27 June 1909, established a School of Marine Engineering. In 1910, Cone reported that the school carried out the intent of the 1899 personnel act and was providing for a small number of designing engineers.

In 1914-1915, Admiral R. S. Griffin, the new Engineer in Chief, pointed out, "The work is progressing in a regular manner under the supervision of the inspectors of machinery, but, as the character of the work is becoming more varied and extensive, the necessity for a larger inspection force is generally apparent. While the present force is able to carry out the work with a fair degree of success, much better results would follow if a more adequate force were provided, both at the offices of inspectors of machinery and at the bureau."

And now we come to the hearings that led to the act of August 29, 1916, which established engineering duty only in the Navy. From the testimony, which was given by Admiral Griffin and others, before the House Committee, it was stated that not as good results were obtained from engines aboard ship under the change as were obtained under the engineer corps because there was not opportunity for complete specialization.

Griffin pointed out that there was fear among the young officers that if they specialized, their future was at stake. Admiral Griffin advocated that officers be permitted to specialize in engineering duty only and that they be promoted when their running mates were promoted and discrimination be removed.

Evidently officers with too much engineering duty had been discriminated against in promotion. As proof, Griffin quoted from Secretary of the Navy report: "A number of officers have developed very high talent in this respect (engineering), but out of justice to themselves and their future careers, they must give up this important work in order to gain experience in deck duties, in order to obtain promotion."

Griffin stated that promotion should not be denied an officer doing engineering duty any more than if he were doing ordnance duty. It was strongly brought out in testimony that the fear of discrimination in promotion was confined entirely to the engineering officer, and he elaborated: "I read what the Secretary said in his report, and that was emphasized recently in the case of an officer who was wanted as fleet or division engineer in the North Atlantic Fleet. He wrote to a senior officer in

the Navy Department and asked his advice. He was advised not to accept the appointment, because it might operate against his future promotion if he went as fleet engineer." The officer governed himself accordingly.

The Committee heard Assistant Secretary of the Navy Franklin D. Roosevelt. He stated, "As a general proposition, it would seem to me that since the amalgamation of the engineers with the line in 1899, the wisdom of the step has been proven. The old Engineer Corps did not work in well into the military machine, and since that time I think the step was not only justified, but the present system ought to be continued as a whole, with certain exceptions. The chief objection to the present system is that a young man in the Navy who goes in for engineering as a specialty feels he must keep up his purely line duties, navigation, ordnance, etc. This has prevented him from specializing as much as he should in engineering. The training which he has had at the Naval Academy, and as an ensign, I consider essential for the bulk of the engineers, but after he has had that preliminary training, he ought to be allowed to specialize. Under this personnel bill, we propose selection, and the selection will be made by the officers of higher rank. The great majority of these officers will be line officers, and if we allow the engineers, the young men who have specialized in engineering, to compete with their line brethren, the chances are that they would never be selected for promotion because they would be specialists and the majority of the line officers above them would naturally prefer an all-around line officer rather than a specialist. That caused us to provide in the personnel bill for these specialists in engineering, ordnance, law and aviation, those four subjects. The most important of those is engineering.

"The effect of this will be twofold. A young man will go into one of these specialties after he has had general service through the Naval Academy and as an ensign, and after he has gone into it, he will stand just the same chance of promotion as if he has stayed in the line. In other words, he will compete not with the line, but only with his fellow engineers, and the same porportion of each will be promoted. We have made it absolutely fair for the specialists. The second point is that those specialists in engineering, ordnance, etc., will be able to devote their whole time to progress in their own specialty, and the result will be much better than under the present system. The engineer officer will not have to spend weeks studying ordnance subjects for promotion. In other words, the professional examination is to be restricted only to the duties to which they are permanently detailed. The engineer officer will only be examined on engineering."

Mr. Roosevelt stated further that they wanted to avoid any staff such as they had prior to 1898 because of the bad feeling between line and staff. In reply to a question concerning the obtaining of men from civil life, FDR stated that he could not help feeling that the academy education and the subsequent experience aboard ships are very essential to the development of a proper engineer or ordnance officer. "He ought to have seven years or more of general naval work so as to understand what it is all about. If you take in a civilian from a scientific school, probably he would make an excellent engineer, but he would not understand the general problems of the service.

So the act of August 29, 1916 provided, among other things: officers for engineering duty only, and it specifically stated that officers of the line of the Navy, not below the grade of Lieutenant, may upon application be assigned to engineering duty only. When so assigned, and until they reach the grade of Commander, they shall perform duty

as prescribed in the 1899 Personnel Act; thereafter, shore duty only as now prescribed for officers transferred to the line from the former Engineer Corps, except that Commanders may be assigned to duty as Fleet Engineers.

In 1920, Admiral Griffin reported, concerning the maintenance of the fleet, that the engineering performance of ships of all types was not satisfactory, due to the personnel situation and the loss of skilled artificer ratings such as occurred during the past year, and the great influx of raw recruits after World War I.

Admiral Griffin stated that the question of commissioned personnel is hardly less serious, and it was undisputed that engineering skill must be part of the line officer's equipment. "During the twenty years under that system, our service has made unexampled progress in all branches of engineering, on the theoretical as well as on the practical side. Now, with addition of large numbers of new ships added to Navy list, it appears that the number of line officers competent to assume charge of the machinery plants of those vessels is far below the number of those available for other line duties of corresponding status. This means, simply, that sufficient engineering experience for all line officers, especially those in the lower grades, has not been enforced."

He further stated that under present conditions, the number of officers doing engineering duty afloat is from ten to twenty per cent of the total number of line officers on the various ships, and he recommended that an average of from thirty to forty per cent of the sea service of all line officers of the lower grades should be spent in engineering duty. If this were done, most, if not all, of the difficulty in connection with engineering personnel would disappear.

In 1921, Admiral Griffin stated with regard to officer personnel, "In recent years—beginning with the adoption of promotion by selection—there has grown up in the service an impression that the performance of engineering duty operates to injure the chances of an officer for selection, while the failure of an officer to have experience in engineering does not operate as a deterrent to selection. It matters not that this impression may be erroneous—it exists, and has grown in strength each year, and unless something of a practical character is done to put the stamp of the Department's approval on the performance of engineering duty, the situation will soon be such as seriously to impair engineering efficiency in the Navy."

In order to correct this condition, he submitted a letter draft for signature of the Secretary of the Navy to the Naval Examining Board, which would make it mandatory that officers coming up for promotion would have certain engineering experience or they could not be promoted.

Evidently the above mentioned letter was never promulgated because no mention was made in the 1922 report. He did state that the personnel situation is believed to have shown improvement during the year due to increased realization among the line officers that engineering duty is essential to complete the education of a successful commanding officer.

He pointed out that the necessity of placing various units of the fleet on fuel allowances brought home the need of increased engineering efficiency within the command, thereby stimulating more interest in engineering duty. Conditions must have improved greatly after 1922 because of the absence of complaints in later annual reports.

And that practically brings us up to date, and there is no need of pursuing the subject further at this time.

However, there are certan conclusions to be drawn from the above recitation

of the history of the Old Steam Engineer Corps amalgamation.

One is that no group or body of officers in the Navy can be singled out or treated differently than any other group with regard to promotion, pay, rank, assignment to quarters, etc. If we are going to have a strong Navy, no group can labor with reduced morale due to discrimination in any form.

No group, by virtue of its employment, can be differentiated against in assignment of quarters on board ship.

No assignment to particular types of duty within the Navy can be, in itself, reason for passing over officers before selection boards. To permit such passovers means that promotion becomes a function of *Bupers* Detail Office and not of a selection board.

Opportunities for promotion in all grades must be the same from a percentage standpoint in any branch of the service since, otherwise, those branches discriminated against will come to be accepted as inferior branches. When that condition exists, officers will avoid assignments in the inferior group, and we lose all chance in this competitive world of obtaining the best personnel and the best material in the discriminated branch. And, as Melville pointed out, the whole is no stronger than the weakest link.

REVIEW OF INTERESTING PATENTS ON QUIETING REDUCTION GEARS

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Graduated from North Carolina State College with a BSEE in 1933. Served in U. S. Merchant Marine. Graduated from Ohio State University with a BME in 1938. Active service in U. S. Navy as a Lieutenant Commander until 1949. Has been employed by the Bureau of Ships in the Turbine and Gear Branch since 1949. Is now staff assistant for research, development and new construction in this Branch. Currently president of The Association of Senior Engineers of the Bureau of Ships and chairman of the Washington Section of The American Society of Mechanical Engineers.

If it became necessary to designate the most important mechanical device in our present civilization, the choice would be a difficult one. Items to be considered would include the paper clip, wheel barrow, handsaw, mechanical hands, engines of various types and many others. A group of outstanding engineers could deliberate over such a selection for many long hours. It is certain, without long deliberation, that one extremely outstanding mechanical development is the reduction gear. No one can dispute the fact that reduction gears are essential in the present pattern of the industrial and domestic scene.

Approximately 100 years ago it is estimated that animals contributed some eighty-percent of our power while man added fifteen percent and machinery accounted for the remainder. There has been a very marked shift in power sources since the year 1850. Man has arranged, through his ingenuity, prompted by a desire for less strenuous effort and an urge to develop new and improved methods, to provide greater power through machines. He has at the same time eased the burden on himself by producing less actual power with his own hands. An estimate of the power developed by animal, man and machine during the years 1850 and 1950 is shown in Table I.

TABLE I. Division of power developed by animal, man and machine in 1850 and 1950.

	Percent Power Developed by		
Year	Animal	Man	Machine
1850....	80	15	5
1950....	12	4	84

TABLE II. Tabulation of Patents Relating to Reduction Gear Noise

Year Issued	Patent Number	Number of Claims	Title
1863	37,634	1	Improvement in Cog-Wheels
1865	48,207	6	Improvement in Carriage-Wheels
1872	126,085	1	Improvement in Railway Car-Wheels
1878	208,580	1	Improvement in Car-Wheels for Electric Railway
1880	228,430	5	Car-Wheel
1881	240,347	5	Method of Absorbing Sound in Wheels
1883	288,134	1	Gear-Wheel
1883	284,290	2	Gear-Wheel
1883	289,771	2	Gear-Wheel
1885	312,780	2	Friction-Gear
1885	314,472	1	Gear-Wheel
1885	4,664	5	Robertson Gearing (British)
1885	315,214	1	Gear-Wheel
1888	379,022	4	Gear-Wheel
1889	403,101	6	Gear-Wheel
1890	426,982	5	Composite-Pinion
1890	429,108	2	Gear Pinion or Wheel
1890	430,818	4	Cog-Wheel
1890	434,949	4	Gearing for Electric Vehicle
1890	435,672	2	Car-Wheel
1890	436,440	11	Electric Motor Car
1891	447,552	6	Cog-Wheel
1891	462,994	1	Cogged-Wheel
1892	474,913	2	Insulated Gear-Wheel
1896	564,214	9	Car-Wheel
1899	623,883	1	Cushioned Car-Wheel
1900	643,134	4	Noiseless Car-Wheel
1901	680,654	3	Rubber Gearing
1903	719,572	1	Gear Wheel
1906	820,789	8	Flexible Toothed Element
1912	1,028,909	6	Gear-Wheel
1912	1,015,870	6	Gear
1912	1,043,012	4	Gear
1913	1,061,770	6	Gear-Wheel
1913	23,367	4	Improvements in Pinions
1914	1,085,420	12	Gear-Wheel
1915	1,163,925	13	Gear
1915	1,124,107	3	Cam-Shaft Drive
1915	1,134,772	2	Speed Change Apparatus
1915	1,136,839	1	Car-Wheel
1915	1,147,805	2	Gear
1915	1,163,926	6	Gear
1916	1,167,742	14	Gear-Wheel
1916	1,180,495	5	Gear

TABLE II. Tabulation of Patents Relating to Reduction Gear Noise (Cont'd.)

Year Issued	Patent Number	Number of Claims	Title
1916	1,185,953	5	Non-Resonant Gearing
1916	1,191,907	1	Gear Body
1916	1,197,261	1	Noiseless Gear
1916	1,203,549	11	Elastic Gearing
1917	1,235,734	1	Noiseless Gear-Wheel
1918	1,265,811	8	Composite Machine Element
1918	1,287,814	15	Gear
1919	1,297,835	2	Gear-Wheel
1920	163,329	1	Improvements in Gear Wheel (British)
1921	1,375,688	9	Resilient Power Transmission
1921	1,329,886	3	Machine Element
1922	1,421,231	5	Machine Element
1922	1,424,203	5	Gear Wheel
1922	1,427,721	6	Noiseless Gear Wheel
1922	1,427,892	2	Gear Wheel
1922	1,436,787	3	Gear Wheel
1925	1,530,072	3	Gear Wheel Silencer
1925	243,518	3	Improvements in Gear Wheels
1926	613,314	1	Device for Silencing Gears (French)
1927	1,618,031	7	Hyde Material
1927	1,622,469	4	Sound Deadner
1927	1,638,118	2	Sound Proofing Gears
1929	1,735,229	13	Timing Gear
1930	347,949	1	Improvement in Gears (British)
1930	1,758,692	3	Gear Construction
1930	1,786,408	2	Transmission Dampner
1931	1,803,293	6	Gearing
1931	1,803,294	5	Gearing
1931	1,803,296	7	Gearing
1931	1,804,906	10	Gear Silencer
1931	1,813,819	2	Gear Wheel
1931	1,819,266	3	Vibration Absorber
1931	1,834,790	3	Power Transmission
1932	1,852,538	4	Damping Means for Gears
1932	1,852,789	22	Damping Means for Gears
1932	390,065	6	Gear Device (British)
1937	2,093,420	15	Gear
1938	2,129,178	8	Car-Wheel
1940	2,207,290	1	Gear-Wheel
1941	2,228,828	1	Noiseless Toothed Wheel
1943	2,307,129	6	Shock Proof Gear
1945	2,380,776	2	Gear Construction
1949	2,460,629	6	Cushioned Planetary Gear
1949	2,460,630	8	Multicushioned Gear
1949	2,492,073	15	Gear Pump

It has been estimated that every American now has at his bidding the energy equivalent of 200 men in electricity and other forms of energy (1). With this tremendous energy supply at the finger tips of everyone reduction gears are a *must.*

Users of equipments set standards of performance that the machines must meet. Absence of unpleasant and disturbing sounds is a requirement for many applications. An automobile with a transmission that generates such gear sounds as to cause discomfort or worry for its occupants is not a dealer's dream. A smooth running and quiet car is attractive. The boats of the tuna fleet cannot afford noise gears in their propulsion plants. Noise transmitted from reduction gear to the water, through the gear mounting or along the propeller shaft, drives away fish that might otherwise go into the hold. Even the electric clock can give forth distracting gear noise to such degree as to keep a person from sleeping. Aside from the domestic applications, we find gears are most essential in equipments not designed for relaxation. Namely, the submarine. Here quiet gears are not merely desired for comfort, but instead are demanded. In many applications aboard submarines reduction gears are used and quietness is needed for successful operation.

Quiet gears are thus sought after for both *comfort* and *necessity.*

The problem of reducing or eliminating noise generated by the meshing of gears is a challenging one. Many individuals, including such outstanding people as the late Henry Ford, accepted the challenge and tackled the problem. The files of the United States Patent Office contain many patents to support the above statement. Inventors of the various methods of quieting gears have certainly spent many long hours devising means of solving their particular noise problems as evidenced by the material presented in patents relating to gear noise.

A number of United States and foreign patents have been studied in connection with the reduction of gear noise. Some of the mechanisms described were most ingenious. Many were relating to methods for transmission of motion rather than power. Others were concerned with silencing wheels of railway cars.

One of the early patents on reduction of gear noise was issued to Franklin A. Morley of Soddus Point, New York, on February 10, 1863, Letters Patent No. 37,634. Mr. Morley devised "A New and Improved Noiseless Cog-Wheel." Thus it is apparent the search for quiet gearing was under way during the days of the Civil War. New ideas were developed and patented in ever increasing numbers from 1863 through the Spanish-American War and World War I.

A number of United States patents issued from 1863 to 1949 on the subject are listed in Table II.

In the following paragraphs some of the most interesting patents are described briefly. The illustrations are taken from the patents as issued and the descriptions refer to elements or parts by letter or numeral as appropriate. The descriptions are generally as set forth in the patents and no attempt has been made to evaluate any of the inventions.

1865—Patent No. 48,207. *Improvement in Carriage-Wheels.* This invention outlines means of "rendering a wheel elastic, so as to relieve the jar and rattle in striking against or passing over stones." The elasticity is achieved by applying a spring or cushion of rubber or other elastic substance between the outer end of the spokes and the wheel rim.

Fig. 2.

U. S. Patent No. 37,634
Feb. 10, 1863
Improvement in cog-wheels.

1863—Patent No. 37,634. *Improvement in Cog-Wheels.* This invention consists of insulating the toothed rim of a gear or "cog-wheel", as the patent describes, by means of a layer of rubber placed between the rim and the central portion of the wheel.

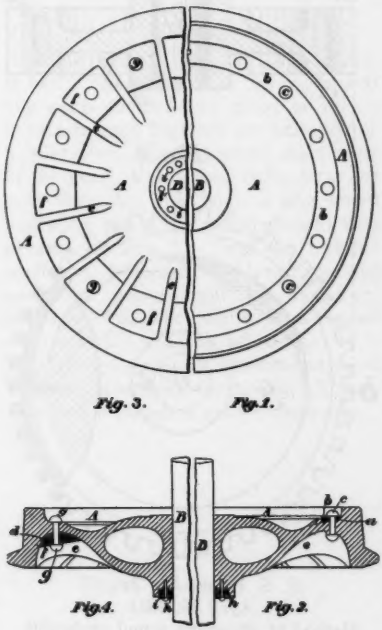
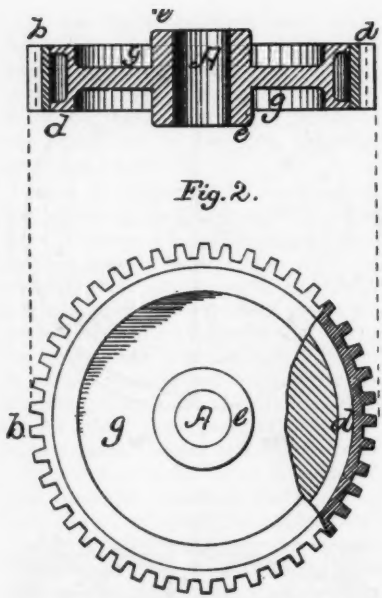


Fig. 3. Fig. 1.

Fig. 4. Fig. 2.

U. S. Patent No. 228,430
June 1, 1880
Car-wheel.

1880—Patent No. 228,430. *Car-Wheel.* The object of this invention is stated "to reduce the noise of running trains and render the car wheels and axles more durable by preventing or greatly reducing the vibrations of the wheel." This is accomplished by fixing dampeners in the form of plates to the wheel near the rim to absorb rim vibrations and thus prevent their transmission to the hub, the axle, bearings and then into the car. These dampeners are composed of rubber or other suitable elastic material *a* and *d* held against the rim by plates *f* and *b* secured with rivets or bolts *g* and *c* as shown in Figures 1, 2, 3 and 4.



U. S. Patent No. 240,347
April 19, 1881
Method of absorbing sound applicable to revolving wheels.

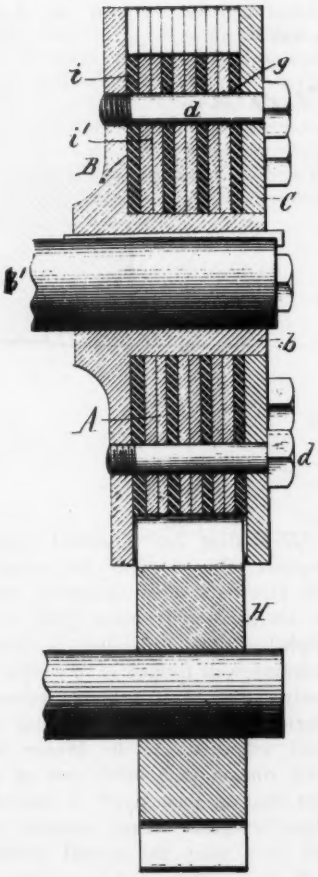
1881—Patent No. 240,347. *Method of Absorbing Sound Applicable to Revolving Wheels.* The inventor states "usual noise from machinery in motion is caused by the resonant vibration of the metallic portions which are acting or working upon each other, such as cog-wheels, loose pulleys, rollers & c." Utilization of elastic cushions to "modify or neutralize these sonorous vibrations, so as to mitigate or prevent noise" is described. These cushions, or deadening substances are listed as solid, fluid, sand, shot. The cushions are placed in the central portion of the wheel. One method is shown in Figure 2. The gear wheel A has an interior annular cavity *d*. The cushioning or deadening material is placed within the cavity *d*.

1883—Patent No. 284,290. *Gear-Wheel.* A gear consisting of a toothed rim of rubber supported on a metal center section is shown by this patent. It is stated that the rubber cogs of the gear engage with the "rundles or cogs" of the mating gear. The rubber rimmed gear is formed by pressing or casting the rubber into a required form and then pouring inside the rim the web and hub section a "white-metal" that fuses at a comparatively low temperature.

1885—British Patent No. 4664. *Improvements in Gearing for Transmitting Motive Power.* Mr. James Robertson states "My invention has for its objective the dimunition of the noise and jar of toothed or cog wheels formed, or cast of metal usually experienced by the use of cog wheels working at high speeds, this object being now so far attained by the use of metal cog wheels having fitted into their rims wooden teeth or cogs having tennons formed on them and passed radially through the rims of the wheels in slot holes or mortises and secured in the same by wedges or pins. The less sonorous nature of the wooden cogs as compared with those of metal greatly reducing the noise caused by the necessarily sharp impact of the cogs of the wheels acting on each other in transmitting power at high speeds."

The invention sets forth methods of constructing and installing *teeth* or *cogs* in wheels with metal rims and centers. The details of attaching the teeth are described. The cogs or teeth are formed in several ways utilizing various materials. Each cog is composed of two parallel strips of wood separated by metal wedges with flat sides. The assembly is made by inserting the wood strips into the wheel and then driving in the wedges. The cogs may be of varied shapes and covered by layers of india-rubber, fiber, leather or other material that will not transmit noise.

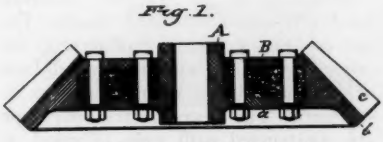
Fig. 1.



U. S. Patent No. 287,711
Oct. 30, 1883
Gear-wheel.

1883—Patent No. 287,711. *Gear-Wheel.* Vulcanized fiber layers, placed one upon another and glued or otherwise cemented together are utilized for a quiet gear. Figure 1 shows main parts of the gear. Vulcanized fibers form the gear body A. This body is first bored and teeth cut in the outer rim and then pressed on hub *b*. Then the metallic washer C is located as shown and the assembly drawn tight by means of screw-bolts *d*. The quiet gear A meshes with metallic gear H as shown. It is cited the gear may be produced at small expense, is adapted for use in all cases in which a noiseless gear is desirable.

Fig. 1.

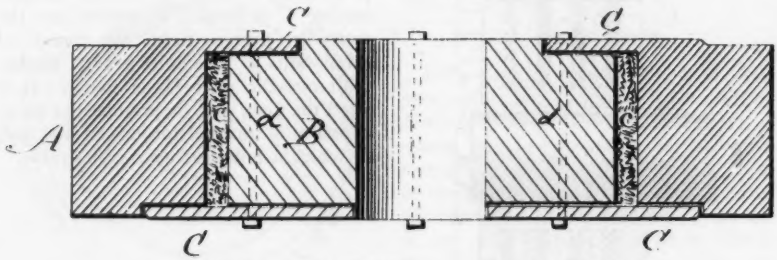


U. S. Patent No. 314,472
March 24, 1885
Gear-wheel.

1885—Patent No. 314,472. *Gear-Wheel.* This invention relates to a method of insulating the rim from the hub of a gear by means of paper. A series of layers of paper C are located between rim *b* and web *a* of a gear in Figure 1.

1883—Patent No. 288,134. *Gear-Wheel.* "It is a well-known fact that in iron-rolling mills where large gear-wheels are used the rattling of the gear teeth produces a roaring noise, which is almost unendurable inside the mills and an actual damage to the value of property for residence in the immediate vicinity." This invention describes a means of insulating the gear rim from the hub by means of "scraps of leather, india-rubber, paper or other insonorous material." The method is illustrated in Figure 2 where *c* is the insulating material between the gear rim A and the hub B.

Fig. 2.



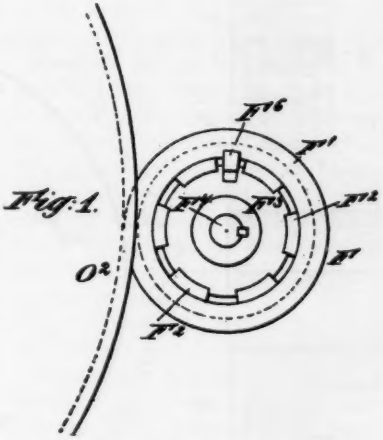
U. S. Patent No. 288,134 Nov. 6, 1883
Gear-wheel.

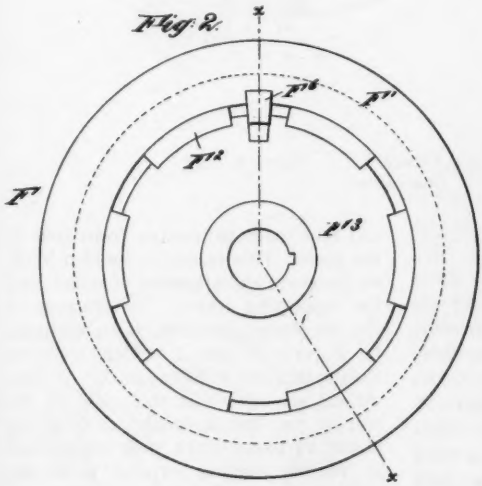
1890—Patent No. 434,949. *Gearing for Electrically-Propelled Vehicles.* The use of spur gears for connecting the propelling motor with the wheel base of electric vehicles or railway cars is set forth. The gears of the spur type are constructed with webs of wood or other non-conducting material so the motor is insulated from the wheel base and the gearing is made less noisy.

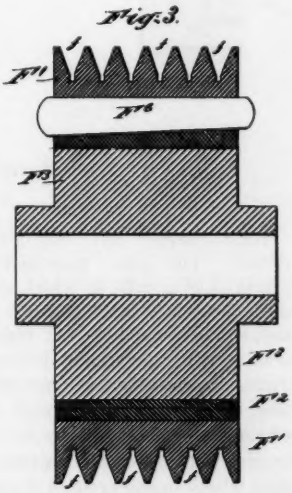
1943—Patent No. 2,307,129. *Shock-proof Gear.* Elimination of shock and noise in gears is the object of this invention. This is accomplished by constructing the gear in such manner that a resilient material is inserted in the body of the disc between the rim and hub. This material may be rubber and it is bonded to the hub and also the rim.

1927—Patent No. 1,622,469. *Sound Deadener.* One object of this invention is to provide a sound deadening structure for gears and wheels. This is accomplished by providing a sound deadening wall formed of a number of loosely packed, relatively non-resonant spherical particles which cause the sound vibrations to be broken and which contact each other only at one point, that is, their point of tangency. Where irregular shaped particles are used as a filler the several particles touch each other along considerable areas and thus transmit a considerable amount of sound. Lead shot have been found suitable. This sound deadening wall, with its spherical fillers, may be bolted to a gear or wheel.

1885—Patent No. 312,780. *Friction-Gear.* Friction gears are suited to work silently and efficiently at high rotative speeds. In order to reduce the difficulty of axial misalignment and reduce noise friction gears with solid metal periphery F, Figures 1, 2 and 3, and solid hub F^3 separated by blocks F^2 of hand rubber or wood are proposed.



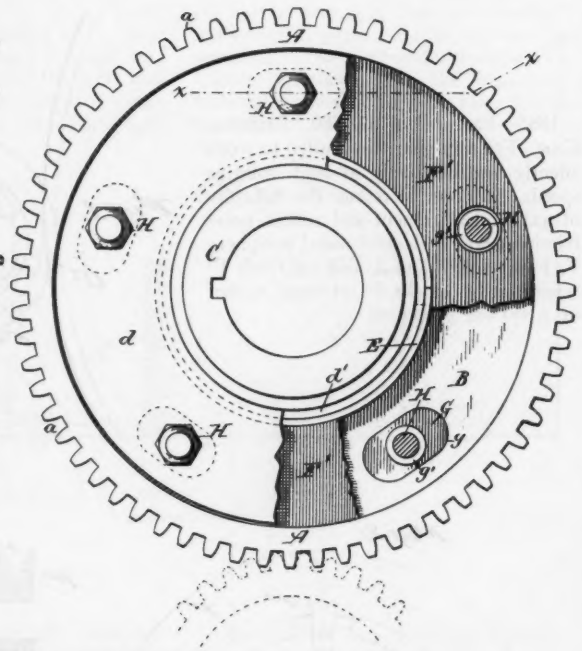




U. S. Patent No. 312,780 Feb. 24, 1885
Friction-gear.

Fig. 1.

Fig. 2.



U. S. Patent No. 379,022 March 6, 1888
Gear-wheel.

1888—Patent No. 379,022. *Gear-Wheel.* The gear described in this patent is of a type in which the rim is made separate from the hub and the support between rim and hub permits some relative movement between these parts. This feature is especially desirable for use in rolling mill gears in which the grinding or crushing rollers revolve with differential speeds, a small gear-wheel being secured to the shaft of the fast roller and a gear-wheel of large diameter to the shaft of the slow roller. As material passes between the rollers friction between the material and rollers tends to cause both rollers to rotate with the same peripheral speed and thus tends to produce front lash in the gears. This results in sudden loads on the gears and vibration of rollers and the supporting frame. The features of this invention consist of elastic cushions G, Figures 1 and 2, which serve to isolate the rim A from hub C. If conditions are such that the speed of the rim or the hub suddenly increase the elastic cushions which were compressed in normal loading expand uniformly upon being less heavily loaded and cause a corresponding acceleration in the hub or rim. In this way the teeth of the mating gear wheels are kept in the contact at all times without any front or back lash. This results in quiet operation.

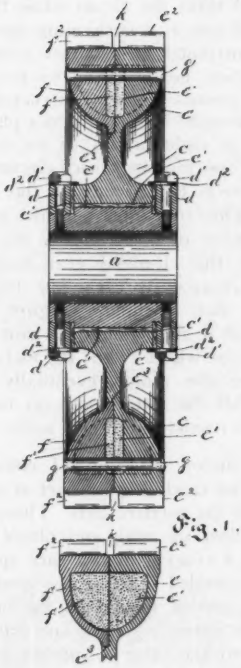


Fig. 1.

Fig. 2.

1889—Patent No. 403,101. *Gear-Wheel.* This gear wheel is intended particularly for use on roller-mills for grain grinding. It incorporates features to prevent noise and rattle common to the ordinary gear-wheel now in use. The unique features shown in Figures 1, 2 and 3 include: leather or rubber isolation c^1 between the hub c and sleeve a; isolation on three sides of keys d; an annular chamber, formed by recesses e^1 and f^1, filled with sand to act as a dampener, teeth e^2 and f^2 of gear rims e and f are so located on assembly that a tooth on part e is directly opposite a space on f; a circumferential space k between the toothed rims.

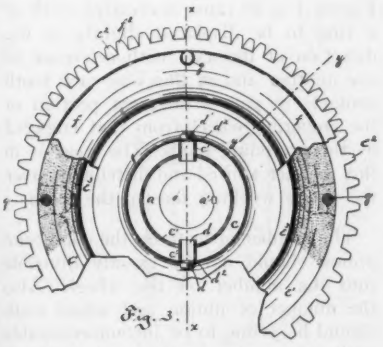


Fig. 3.

U. S. Patent No. 403,101
May 14, 1889
Gear-wheel.

1931—Patent No. 1,813,819. *Gear Wheel.* An object of this invention is to provide a non-resonant gear wheel. This is accomplished by so constructing the gear wheel that there are provided inwardly projecting walls at the two sides of the tire or rim of the wheel which form with the inner surface of the tire or rim an inwardly facing pocket. The gear casing is supplied with sufficient oil or grease so that when the gear is rotating the pocket will become filled with oil or grease. When such condition exists the gear wheel becomes non-resonant, all ring being taken out of it.

Fig. I.

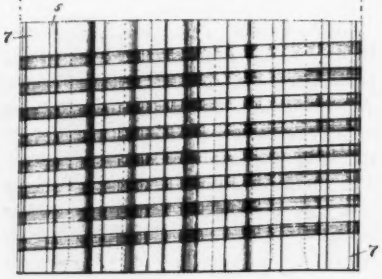


Fig. IV.

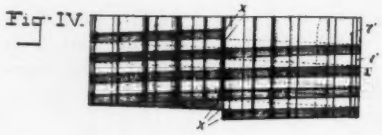
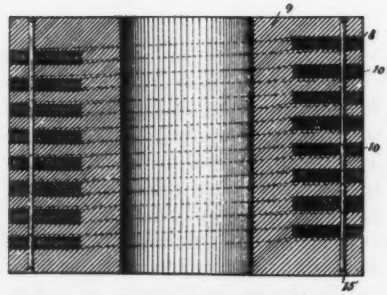


Fig. V.



U. S. Patent No. 426,982
April 29, 1890
Composite pinion.

1890—Patent No. 426,982. *Composite-Pinion.* This invention relates to an improved construction of composite pinions formed of alternate layers of metal plates or other hard material and comparatively soft or non-resonant material such as rawhide. The hard material takes the strain while the soft material acts as a cushioning agent and thus contributes to smoother action and a noiseless gear. Prior to this composite pinions were constructed with their alternate layers or plates placed in planes at right angles to the rotative axis. These pinions caused circumferential grooves to be worn in the mating gear. This invention permits an even distribution of wear across the entire face of the all-metal gear tooth and thus increases its life. The layers of metal[1] and rawhide[2], Figure 3 are placed at a slight angle or cant to the axis of the wheel. Thus the metal tooth area on the pinion eventually travel across all the metal tooth on the gear and this results in uniform wear.

The pinion in Figure 1 consists of metal and rawhide plates set at a slight angle to the rotative axis. These plates are backed up with end plates 7. In Figure 4 rings 1′ and 2′ are split and then assembled to form two continuous helices, one of metal and the other of rawhide, extending from one end of the pinion to the other. Another form of construction is shown in Figure 5 and consists of cutting a helical groove 8 in a solid wheel 9 and then winding rawhide band 10 into the groove.

The effect of construction as shown in Figure 1 is to cause successive teeth of a ring to be displaced slightly in the direction of the axis with reference to one another and in this way each tooth contacts in part a different portion of the engaging wheel from that engaged by the preceding tooth. The wear is in this manner shifted and distributed over the entire working face of the tooth.

The number of teeth on the composite pinion should not be exactly divisible into the number on the wheel. Also the number of pinion and wheel teeth should be prime to or incommensurable with one another so that each tooth on the pinion shall be brought into contact with each tooth on the gear.

FIG. 1.

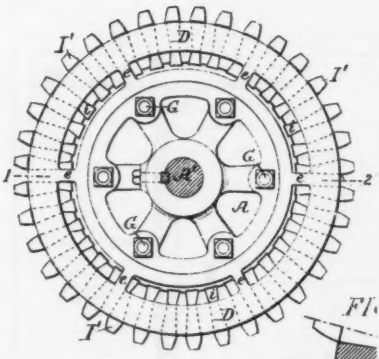
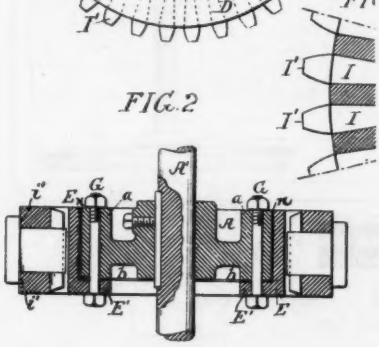


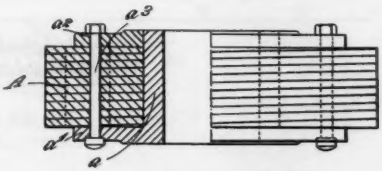
FIG. 2.



U. S. Patent No. 430,818
June 24, 1890
Cog-wheel.

1890—Patent No. 430,818. *Cog-Wheel.* A sectional cog-wheel especially suited for use with electric motor-driven cars is described. The teeth are detachable. Use of an elastic packing material between the outer and inner portion of the gear affords a sound dampener. Figures 1, 2 and 6 show the main features of the gear described. The gear is mounted on shaft A′. The center portion A of the gear has spokes *b* connecting to outer ring *a*. The gear rim B consists of outer ring D and inner ring E. Radial tapered openings *g* are formed in D. The gear teeth I, preferably made of hardwood are inserted in the openings *g* and fixed in place by wedges H. An elastic packing *n* acts as a sound deadener.

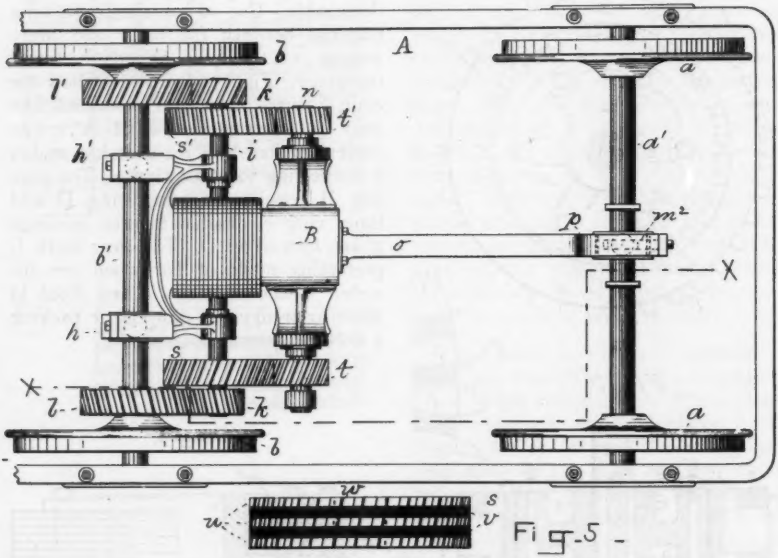
Fig 7.



U. S. Patent No. 1,028,909
June 11, 1912
Gear-wheel.

1912—Patent No. 1,028,909. *Gear-Wheel.* A method is described in this patent whereby a gear is manufactured from a strip of metal wound in the form of a coil. The convolutions of the coil are in contact with each other. The convolutions are secured together by suitable means such as rivets. The coil is wound upon a mandrel while the strip is hot. The coil ends are faced and the coil A assembled on the hub *a*, the end plate a^2 installed and the assembly held secure by the bolts a^3 as shown in Figure 7.

Fig. 1



U. S. Patent No. 436,440 Sept. 16, 1890
Electric-Motor Car.

1890—Patent No. 436,440. *Electric Motor Car.* Means for producing noise-free operation of electric driven railway cars are described. Wheels and gears are considered. Rubber mountings are used to isolate wheels from axles. The gear wheels *ll'* Figure 1 on axle *b'* have teeth cut diagonally, in opposite directions on each wheel. The pinions *kk'* have diagonally cut teeth. The corresponding gear-wheels on each shaft have their teeth cut at opposite angles. When diagonally cut teeth begin to mesh they first come into contact at a corner and the contact then gradually moves across the whole side of each of the two mating teeth. This movement causes the gearing to run with comparatively little noise. The gears are constructed of alternate layers of metal and vulcanized fiber or other substance that act as dampeners or absorbers of sound. These layers are riveted together and then the teeth are cut. The metal affords strength, and the fiber acts as a dampener and gives a *softness* of touch between mating gears. The diagonal cut of teeth on this built up gear makes it more noiseless than a similar gear with teeth cut in the usual manner, straight across the periphery of the wheel.

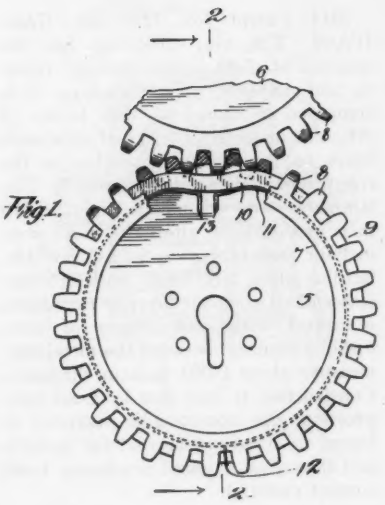
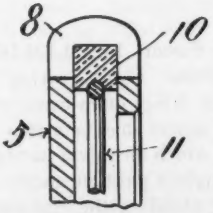


Fig. 1.

8 in Figure 4, at the base of its teeth. This channel is so constructed that space between the teeth 8 extend into the channel. In the channel is mounted a yielding substance 10 which projects into spaces 9 between adjacent teeth, at the base. A spring 11 forces this substance into space 9. In Figure 1 this substance 10 is shown depressed as a gear 6 of usual construction meshes with the gear incorporating the noise reducing features disclosed by this invention.

Fig. 4.



U. S. Patent No. 1,015,870
Jan. 30, 1912
Gear.

1912—Patent No. 1,015,870. *Gear.* The purpose of this invention is to provide means for absorbing the chatter and noise produced by intermeshing gears. This is accomplished by designing the gear with a circumferential U-shaped channel, such as that at 10 and

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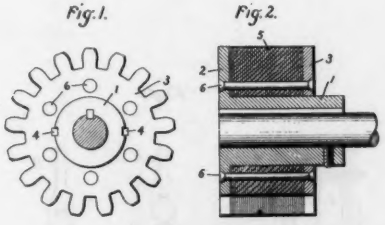
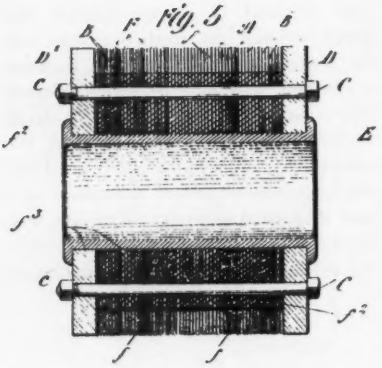
Fig. 1. Fig. 2.



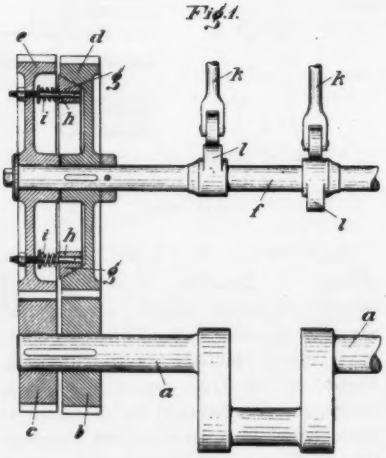
U. S. Patent No. 1,061,770
May 13, 1913
Gear-wheel.

1913—Patent No. 1,061,770. *Gear-Wheel.* A noiseless or non-resonant pinion or gear wheel, strong and durable, is described. This pinion is made up of spinnable textile fibers 5, Figure 2, cut from batten or layers, which are then stacked on gear hub 1. End plate 3 and rivets 6 then complete the fabrication which is done under pressure. Teeth are then cut in the rim of the gear as in Figure 1.



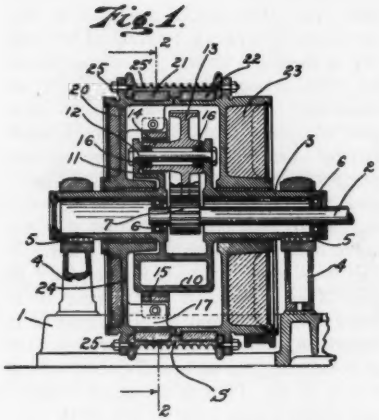
U. S. Patent No. 1,085,420
Jan. 27, 1914
Gear-wheel.

1914—Patent No. 1,085,420. *Gear-Wheel.* The gear described has the qualities of silent action, strength, rigidity and simplicity of manufacture. It is composed of numerous thin layers of different materials alternated with each other to form a gear similar to the construction shown in Figure 5. The laminates are of metal, about 0.010 inch in thickness, alternated with non-metallic substances such as rawhide, muslin, paper, silk, brass, cork or other material. A complete layer of two sheets of metal with four sheets of non-metallic material between the metal may measure about 0.060 inch in thickness. Construction is such that by axial compression the non-metallic material is forced to stand out beyond the metallic and thus give a sound deadening tooth contact material.



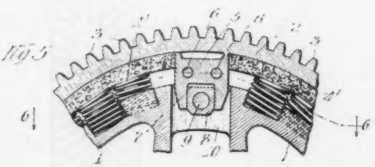
U. S. Patent No. 1,124,107
Jan. 5, 1915
Cam-shaft drive.

1915—Patent No. 1,124,107. *Cam-Shaft Drive.* Spur gearing used in cam-shaft drives often cause continuous rattling noises due to action of valve springs, which on valves having exceeded the highest position, causes a sudden jumping ahead of the cam-shaft. This results in acceleration of the spur gear on this shaft and the faces of gear teeth on this shaft *e* hit against the opposing rear faces of teeth or the driving gear on the crank shaft *a*, Figure 1. This noise is suppressed by placing the driving wheel under a continuous braking action.



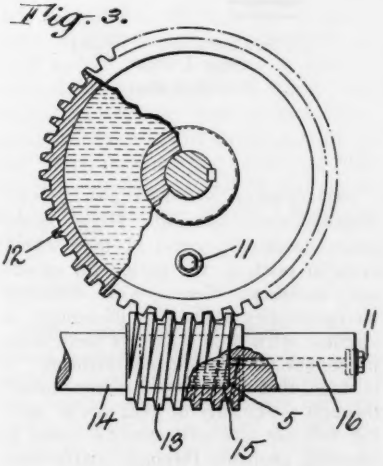
U. S. Patent No. 1,134,772
April 6, 1915
Speed changing apparatus.

1915—Patent No. 1,134,772. *Speed Changing Apparatus.* The speed changing device shown in Figure 1 incorporates several noise reducing features. Sheave S is formed with double walls and thus provides spaces 20, 21, 22 and 23 which can be filled with a noise deadening material.



U. S. Patent No. 1,163,925
Dec. 14, 1915
Gear.

1915—Patent No. 1,163,925. *Gear.* The toothed rim of this gear is separated from the central portion and sound isolating material is interposed between the rim and the web or center to reduce and eliminate noise. There are several forms of construction. One method is illustrated in Figure 5. The central portion 1 supports the toothed rim 2 through springs 4 which are in contact with sound deadening material 4. To limit radial displacement and circumferential movement between 1 and 2 a number of lugs 5 are attached to 2 and are guided by lugs 8 pivoting on pin 9 attached to the gear center. The construction will apply to helical as well as to spur gearing.



U. S. Patent No. 1,185,953
June 6, 1916
Non-resonant gearing.

1916—Patent No. 1,185,953. *Non-Resonant Gearing.* The noisy operation of spur gearing may be greatly reduced or practically eliminated by constructing the gear with an annular chamber or compartment Figure 3 and filling with a liquid such as oil or water. The liquid is under pressure and will act to absorb or prevent vibrations.

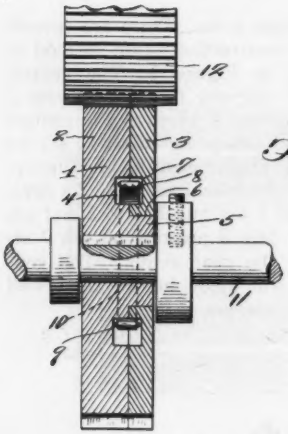


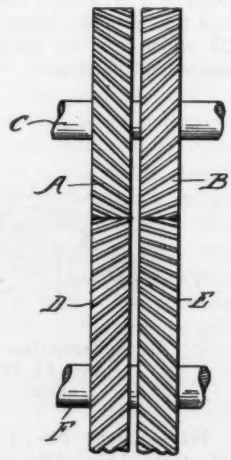
Fig. 1.

U. S. Patent No. 1,197,261
Sept. 5, 1916
Noiseless gear.

1916—Patent No. 1,197,261. *Noiseless Gear.* The device disclosed by this invention concerns a method of producing a noiseless gear. This is achieved by eliminating the noise known as clocking. The invention consists of a pair of gears 2 and 3, Figure 1, each having corresponding diameters and pitches. Gear 2 has a cylindrical boss 5 and an annular depression 4. Gear 3 has a circular opening 6 that will receive boss 5 as assembled in Figure 1. Pin 8 is fixed to gear 3 and pin 9 to gear 2 as shown. A leaf spring 10 is fitted to pins 8 and 9. The gear 2 is keyed on shaft 11 while gear 3 is free to rotate slightly on boss 5 due to spring action of 10. Thus when gears 2 and 3 are meshed with gear 12 the teeth on 2 and 3 contact opposite faces on gear 12 and the "clocking" noise incident to meshing is avoided.

1931—Patent No. 1,803,294. *Power Transmission Gearing.* High speed gears develop a sound or tone which rises in pitch as the peripheral speeds are increased. Gears with different characteristics such as differences in circular pitch or in angle of teeth have individual tone producing qualities. It is stated that when power is transmitted through a plurality of gear trains having different characteristics the sound is lessened, probably through interference between vibrations of different frequencies having a neutralizing effect on each other. The differential characteristics described in this invention is a difference in pressure angles of teeth in two trains. In Figure 1 A and B are mounted on a common shaft C while D and E are on Shaft F. The two trains are of equal ratios but different pressure angles. Thus teeth in gears A and D may have a pressure angle of ten degrees while teeth in B and E may have a pressure angle of twenty degrees.

Fig. 1



U .S. Patent No. 1,803,294
April 28, 1931
Power transmission gearing.

Fig. 1.

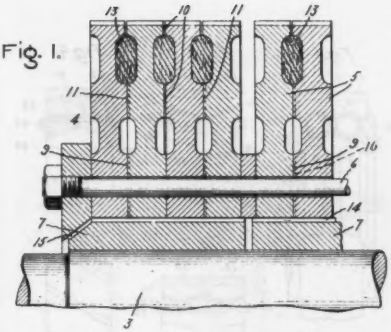
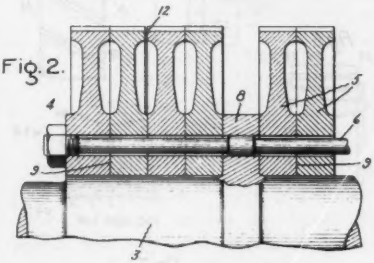


Fig. 2.



U. S. Patent No. 1,203,549
Oct. 31, 1916
Elastic Gear.

1916—Patent No. 1,203,549. *Elastic Gearing.* Elastic spur gearing built up from a number of disks 5, as in Figures 1 and 2, and clamped or bolted firmly together at their central portion with provision for axial movement between the disks at their peripheries. The object is to form means for absorbing or preventing vibration of the gears and thus reduce noise. The gear wheel 4 is mounted on shafts 3. The wheel is composed of a number of disks 5 held together by bolts 6. In Figure 1 the disks are mounted on sleeves 7 which may be keyed to the shaft. In Figure 2 the disks are secured to piece 8. Disks are arranged in pairs with points of contact 11 selected where relative movement occurs. Groups are separated as at 10 and 12. Vibration may be further reduced by introducing semi-elastic substances such as felt, cloth or rawhide as at 13 in Figure 1. Oil under pressure is also introduced at the center of the wheel by grooves 14 and 15 and flows out through passage 16 and a damping action results.

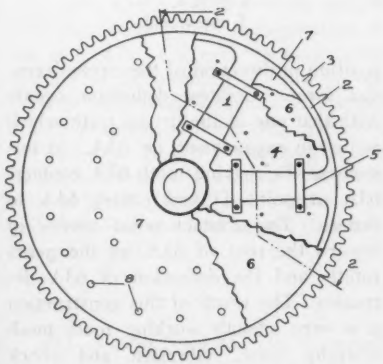


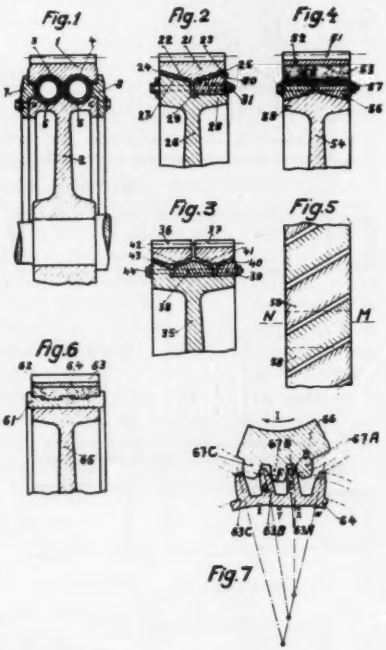
Fig. 1

U. S. Patent No. 1,530,072
March 17, 1925
Gear wheel silencer.

1925—Patent No. 1,530,072. *Gear Wheel Silencer.* Roaring noises produced by gears of large diameter having long spokes and rim sections can be sound deadened. To avoid transverse vibrations and consequent roaring a filler 4 is inserted in the segmental spaces as in Figure 1. The filler may be built up of boards equal in thickness to the spokes. The filler is made to fit closely between the edges of the spokes and inner rim 2. Outside the filler 4 a layer of non-sonorous material such as builder's tar felt covering 4 and the spokes is placed and held in position by disk cover 7. The disk 7 is held by bolts 8. Lateral or drum head vibrations are cleaned by the elastic or non-sonorous layers of felt that overlie the sides of the spokes and of the segmental fillers.

1922—Patent No. 1,424,203. *Gear Wheel.* Composite gear wheels incorporating features designed to contribute to noiseless and smooth operation and long life are described. A basic concept is that of an immediate ring interposed between the toothed rim and the wheel disc. This ring may be of a material that is soft and elastic as compared to metal. Rubber or leather may be used. One type, shown in Figure 1 shows the inner ring to consist of two air tubes 3 and 4 between toothed rim 1 and disk 2. These air tubes are inflated and exert radial pressure on rim and disc. Another configuration is shown in Figure 4 where rim 52 is separated from disc 55 by rubber ring 53.

Figure 6 illustrates one form of composite wheel where all parts are cylindrical. It may be constructed by casting a rubber ring 62 onto a base ring 61. The toothed rim consists of a thin ring 64 with teeth 63. The toothed rim is shown in large scale in Figure 7. The teeth 63A, 63B and 63C of the driven wheel are nearly half as high again and are at the root thinner by one third as compared with the teeth 67A, 67B and 67C of the driven wheel 66. Wheel 66 rotates in direction of arrow I and is rigid in view of its short and stout teeth 67 as compared with the toothed rim 64. The teeth 63 can be deflected in direction the circumferential force, i.e. towards the left, due to their great height and narrow root. This circumferential force effects, due to great leverage, a deflection of the thin rim 64 into an "S" shape w-x-y-z so that the teeth of the driven wheel, which are in engagement at the moment are deflected still further out of their initial unloaded position in direction of the circumferential force. Greatest deflection occurs with that one of the driven teeth which is just in engagement, i.e. 63A. At this moment the driving tooth 67A contacts 63A at point D and causes 63A to deflect. The contact point moves in toward the root of 63A, as the gears rotate, and the deflection of 63A decreases. The result of this construction is a very smooth working tooth mesh whereby noise, vibration and shock stresses resulting from manufacturing inaccuracies are reduced to the smallest amount.



U. S. Patent No. 1,424,203
August 1, 1922
Gear wheel.

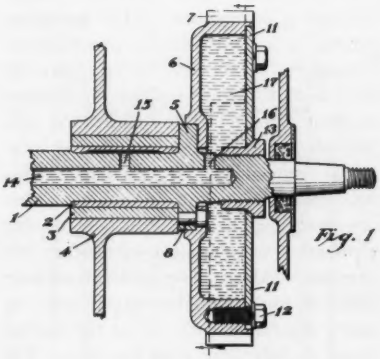


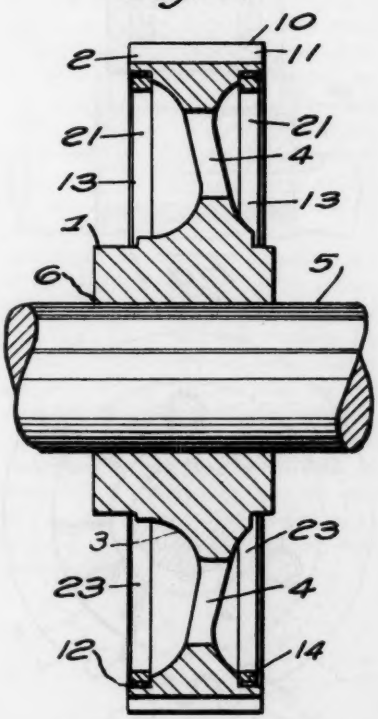
Fig. 1

U. S. Patent No. 1,638,118
August 9, 1927
Means for soundproofing
gear mechanisms.

1927—Patent No. 1,638,118. *Means for Sound-proofing Gear Machinery.* This invention relates to means for sound proofing gear mechanisms and reducing noise incident to operation of gears not wholly immersed in oil. It has been found that if a body of oil is kept in contact with the parts of a gear ring which carries the gear teeth, though not with the teeth, the noise which otherwise accompanies the operation of the gear will be greatly reduced. One method of maintaining a body of oil, fluid or semi-fluid substance in contact with a gear rim is illustrated in Figure 1. The gear ring 6 is attached to the flange 5. Plate 11 is secured to the ring 6 by bolts 12. Oil 17 enters channel 14 and flows into the lead 16 and then into the gear cavity.

1932—Patent No. 1,852,538. *Dampening Means for Gear Wheels.* A damping device for absorbing the vibrations of a gear wheel rim is described. These vibrations may be suppressed, or damped, by applying non-sonorous material 12 to the inside of the rim 2, Figure 4. This material is of such nature that it will absorb and dissipate the energy of vibration of rim 2. The dampening material 12 should be applied in a continuous strip, in the form of an annulus. A pair of retaining springs 13, of wrought iron or other suitable material, are used to hold the dampening material in firm contact with the inner surface of rim 2.

Fig. 4.



U. S. Patent No. 1,852,538
April 5, 1932
Damping means for gear wheels.

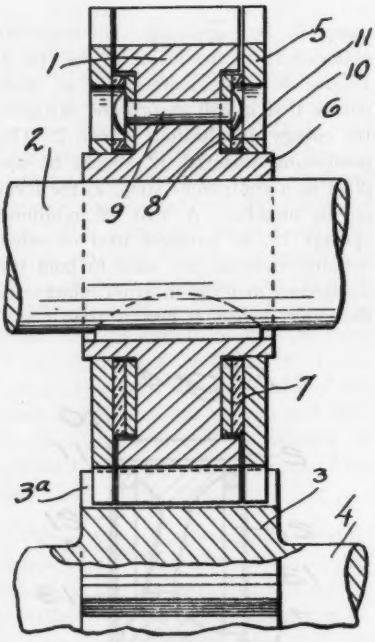


Fig 1

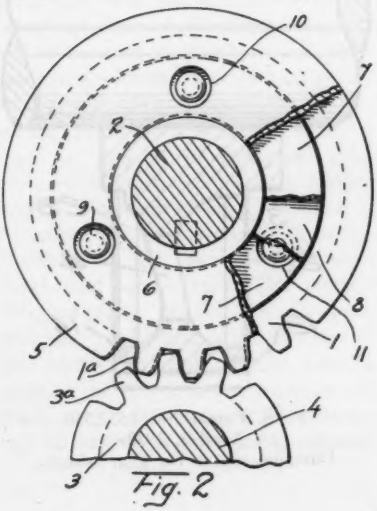


Fig. 2

1931—Patent No. 1,804,906. *Gear Silencer Construction.* This invention relates to a gear silencer construction. Clearance is allowed between mating gear teeth to assure freedom of rotation without binding. Such clearance also permits small amounts of relative rotational movement, or backlash. This movement can result in noise. Means are described here to hold the mating elements snugly against each other and prevent backlash. The backlash silencer consists of a complementary gear or gears associated with one of the mating gears and meshing with the other. The complementary gear 5, Figure 1, is narrow faced and piloted on shoulder 6 of gear 1. The complementary gear 5 is connected to gear 1 in such manner that the teeth of the two gears are staggered relative to each other. A rubber, a disk or ring, 7 is used. Gears 1 and 5 are so staggered that when meshing with a gear 3, Figure 2, teeth 1 a contact on one side of the groove defined by two teeth 3a, while teeth 5a contact with opposite sides of the groove. At this time the rubber element 7 is in tension so there is a snug yet yielding engagement between the complementary gears 1 and 5 and the gear 3.

U. S. Patent No. 1,804,906
May 12, 1931
Gear silencer construction.

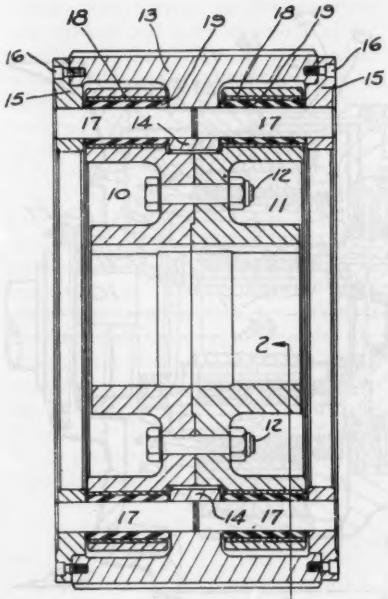


FIG. 1

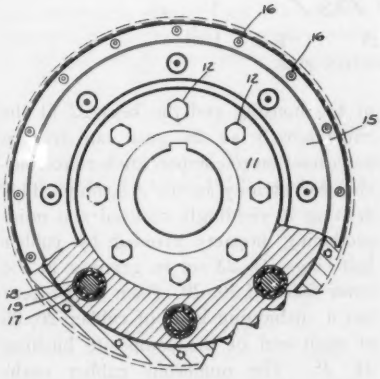


FIG. 2

U. S. Patent No. 2,460,630
Feb. 1, 1949
Multicushioned gear.

1949—Patent No. 2,460,630. *Multicushioned Gear.* The primary objects of this invention include quiet operation, simplicity and economy of construction and assembly. One type of construction embodying the methods described is shown in Figures 1 and 2. The gears shown comprise a pair of axially abutting hub members 10, 11 secured together by bolts 12, 12, an externally toothed member 13 formed at the middle of its inner periphery with an inwardly projecting annular web or series of lugs 14 and, a pair of annular, inwardly projecting side plates or rings 15, 15 secured to the respective annular sides of the toothed member 13 by screws 16, 16. The web 14 of the part 13, the side rings 15, 15 and hub members 10, 11 are formed with a circumferential series of sets of aligned holes for the reception of pins 17, 17 of a series of pairs of cushioning assemblies each comprising a pin 17, a metal shell 18 surrounding and spaced from the pin, and a cushioning rubber bushing 19 mounted, preferably under radial compression, between the two.

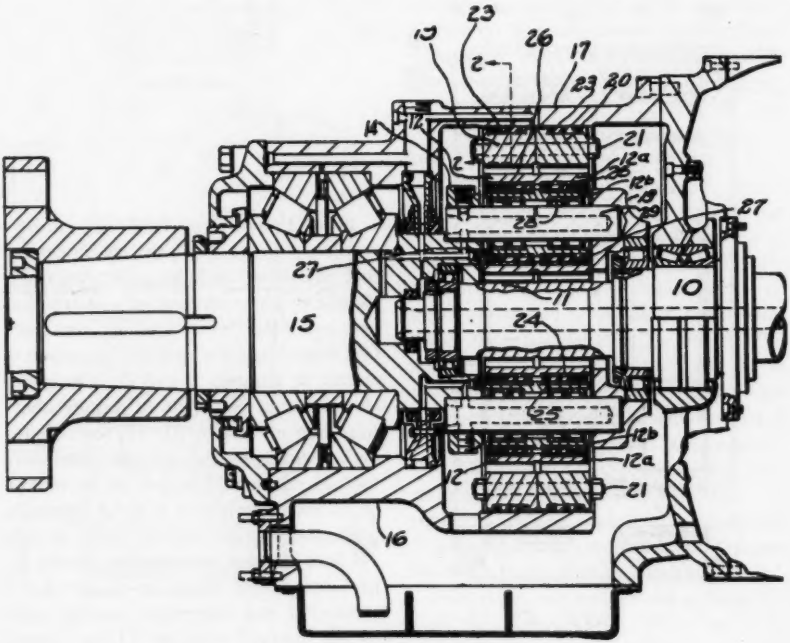
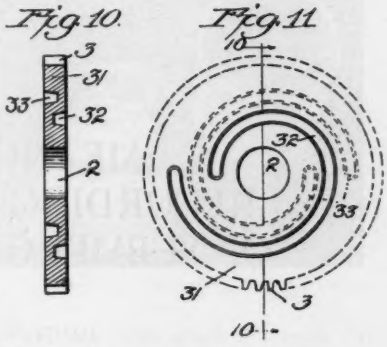


FIG. 1

U. S. Patent No. 2,460,629 Feb. 1, 1949
Cushioned planetary gear.

1949—Patent No. 2,460,629. *Cushioned Planetary Gearing.* A method of assuring equal division of torque among planets of a planetary gear, even though inaccuracies exist, is described. One of the chief objectives is to reduce noise and the emission of sound. The gear is composed of a driveshaft 10, Figure 1, having a sun gear 11 attached, a set of planet gears 12 mounted in a two-part cage or spider 13, 14, of which 14 is integral with a driven shaft 15. Ring gears 19, 20 are of smaller diameter than the adjacent cylindrical inner face of the housing and the keys 22 fit the rings loosely so the gear can drift in any direction to compensate for unavoidable eccentricity in the assembly. This drifting is yieldingly resisted and noise producing impacts avoided by rubber half-rings 23, 23 set in grooves in the outer faces of 19, 20. Each planet gear has a cushioning body of rubber 26, 26 of each end of the composite bushing 24, 25. The numerous rubber cushions provide a sound deadening effect and assure equal distribution between planets.

1940—Patent No. 2,207,290. *Gear Wheel.* The purpose of this invention is to control and lower the pitch of the sound produced by a gear wheel while in mesh with and transmitting power to another gear. The pitch of the sound produced by meshing gears depends upon the length of the path which vibrations must follow from the toothed rim to the shaft on which a gear is mounted. The length of this path in the case of a plain disc wheel is the radial distance between rim and shaft. This path is lengthened by constructing the gear wheel with annular troughs extending into the disc from opposite faces, the troughs and disc being concentric, each trough being of a depth greater than one-half the thickness of the disc, and the radii of the troughs being different. This construction is illustrated in Figures 10 and 11.



U. S. Patent No. 2,207,290
July 9, 1940
Gear wheel.

CONCLUSION

In this review of patents relating to the silencing of reduction gears it is hoped that those concerned with the subject may find something of interest and value. A study of old ideas often uncovers a scheme that is usable while at the time of its conception it was impractical due to lack of engineering know-how on related and supporting components. The gas turbine is cited as an outstanding example of a new idea that was impractical for more than one hundred years after its invention because of poor materials.

REFERENCES

1. "The Romance of Power and Fuels"—J. E. Tobey, *Mechanical Engineering*, v. 74, n. 10, October 1952, pp. 812-815.

METHOD FOR RECORDING ROUGHNESS OF SUBMERGED SURFACES

JOHN W. SAWYER

The study of the geometrical conditions of working surfaces of machine parts has resulted in the development of many methods, instruments, standards and techniques during recent years (1). The importance of the subject is indicated by the extensive efforts made by industry in this country and abroad to determine the effects of finish on the performance of equipment.

Instruments and methods that have been developed (2) include the micro interferometer, Brush Analyzer, Profilometer, Talysurf, Tomlinson Recorder, Bean Comparator, Comptor, Comparascope, Dual Microscope, Herschman's Method, comparators, tapersectioning, light slit method, photographic techniques, ping pong ball method, photoelectric method, pneumatic devices, proficorder, reflection meter, rugosimeter, Schmaltz method, shadow casting, stereomicroscopy, straight edge shadow method, surfascope, Tretini tester, dye-in-solution method and others.

Replicas have been utilized to record accurate three dimensional conditions of surfaces. Pliable films such as the well known Fax-Film (3), are used with good results and inspections are made by projecting the film onto a screen for visual study. Rigid replicas are also finding wide application. Materials for making castings onto surfaces to produce rigid three-dimensional records include plaster, wax, low temperature melting alloys, sulphur-graphite mixtures and a thermo setting resin that cures at room temperature without the application of external heat or pressure.

Inspection of surface finish must be made under a wide variety of conditions. The instrument and technique finally selected depend, generally, on a number of factors including: (a) nature of the surface (b) instruments available (c) accessibility of the area to be studied (d) portability of the part and (e) accuracy required. In order to check the surface finish of a turbine blade as it comes from the production line an inspector could take the blade to an instrument located in the inspection room at the plant. However, to inspect this blade after it has been in operation in a turbine for six months the problem is not simple. It may be very expensive and highly impractical to measure the finish on the blade unless

it can be done at a time when the turbine casing has been lifted for other work. Even then instruments must be transported to the turbine or replicas made and sent to the inspection room for measuring.

Inspection of areas, such as blade surfaces mentioned above, can be achieved. However, the cost and time involved may often be prohibitive. There is one type area that has remained beyond the scope of surface checking instruments and techniques without changing the surrounding media. That surface may be classified as a submerged surface. Many surfaces will fall into this category including the wetted surface of a ship's hull, the interior of an oil storage tank, the wall of a water main or corrosion test specimen submerged in sea water. These areas, depending on location, surrounding conditions, size and other factors may present insurmountable problems in measuring surface roughness by conventional methods.

The Bureau of Ships, several years ago, developed a method of recording the *actual* contours of the surface of a machine part to aid in studying wear of reduction gears. This method (4) consisted of producing a rigid three-dimensional replica of the surface under study. The material finally selected was a plastic, a free flowing polyester resin, that could be easily stored, prepared for use and cast in a relatively short period of time. A resin was developed to meet the requirements of: handling by inexperienced personnel, use of simple equipment, cure without the application of external heat or pressure, cure in about thirty minutes, reproduce accurately and be rigid to permit handling (4). This resin, now available under the name Marcokit MR-249, was packaged for field use in preweighted amounts in two-compartment containers Fig. 1.

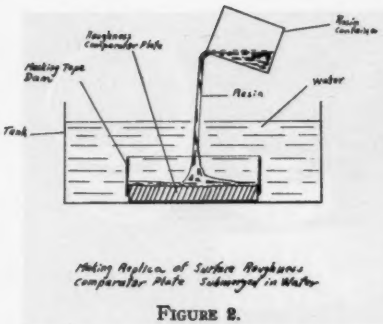
FIGURE 1.

The ease with which this resin can be handled and accuracy of replicas led the writer to consider it as a means for producing replicas of surfaces submerged in water, oil, and other fluids.

A simple test was conducted to determine whether the resin would cure under water. A small quantity of resin and catalyst were mixed according to instructions. The mixture was then poured onto a surface comparator plate submerged in tap water. The comparator plate was arranged with a dam of masking tape around its four edges as in Fig. 2. The resin cured in about thirty minutes. The replica and comparator were removed from the water. Upon visual examination and comparison the replica was found to be an accurate reproduction. In a few hours the replica cast on the submerged plate was as hard as one that had been cast in air from the same batch of resin.

Following this first attempt to produce a replica of a wetted surface it was decided to conduct test under various liquids. Tests replicas were cast on surfaces submerged under the following:

Tap water
Tap water and sodium chloride mixture
SAE 30 lubricating oil
Tap water, salt and SAE 30 oil mixture



Making Replica of Surface Roughness Comparator Plate Submerged in Water

FIGURE 2.

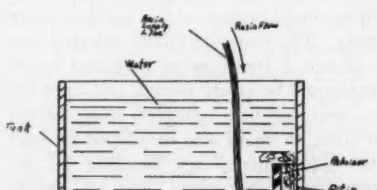
The tests were made on specimen arranged as in Fig. 2. The replicas were satisfactory and from a visual inspection were good reproductions. The data from a typical casting operation is listed below:

Test specimen—aluminum
Specimen submerged in water
Room temperature 68°F
Water temperature 80°F
Resin—Marcokit MR-249
Resin and catalyst mixed at 8:29 PM
Casting in water at 8:30 PM
Replica removed at 8:45 PM

Replicas produced from the MR-249 resin are hard and can be handled as soon as they are removed from the surface under consideration. However, it has been found desirable to permit several hours to lapse between the time the replica is removed and the inspection with a stylus type instrument. A safe practice is to wait 24 hours before subjecting the replica to the travel of a stylus. If the stylus is passed across the replica several times before the resin has hardened the peaks will be smeared and smoothed over. This will result in false roughness values.

The development of a resin (4) for the purpose of studying wear has resulted in a material that may find applications quite different from those first considered. The fact that this resin, and there may be others capable of matching its performance, will set under water and oil as mentioned above suggests a variety of uses. Inspection of hulls, tanks and pipes appears feasible. Methods for conducting inspections, production of replicas, of these three items can be varied. In order to give some ideas as to the technique that may be necessary a suggested procedure for each of the above items is described in the following paragraphs.

Tank Wall—Replicas of a vertical wall surface such as that of a water tank, Fig. 3, may be produced. A retainer with resin supply line attached is submerged and placed against the tank wall. The retainer in this case may have an open top. It can be held to the tank by suction cups, magnets if the tank material is magnetic, or by extension arms through which manual pressure is applied from an operator at the tank top. After the retainer is in place resin and catalyst may be mixed and then forced through the resin supply line into the retainer. As the resin flows into the retainer it settles and water is displaced. The resin is allowed to harden for 30 to 60 minutes depending on conditions. The replica may then be removed and a rigid three dimensional record of a submerged area is available for study.



Method For Making Replica of Vertical Wall Section Submerged in Water

FIGURE 3.

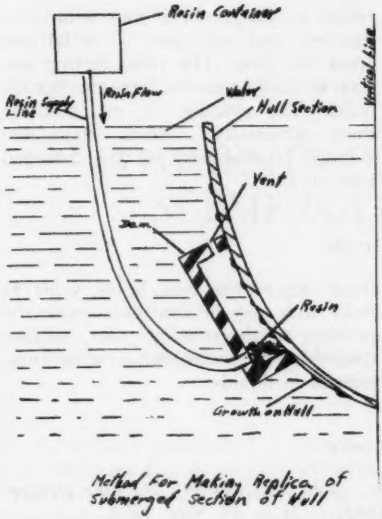


FIGURE 4.

Ship hull—The procedure for making a plastic replica of a submerged hull area is basically the same as that for the tank wall described above. With surfaces that are not vertical the problem is more difficult. It appears feasible, however, to set and hold, Fig. 4, by suitable hauling lines, a retainer against a submerged hull area. Once the retainer is in place resin may be forced in through the supply line. Water escapes from the retainer through suitable vent holes as shown. The resin flows into contact with the hull surface. After hardening the retainer and replica are removed. The replica then provides a three-dimensional record that can be explored in the laboratory with surface roughness measuring instruments as necessary.

Pipes and tubes—Confined area such as presented by pipes and tubes require a somewhat different type of dam or retainer from those described in the preceding paragraphs. Sections less than one inch diameter may not be

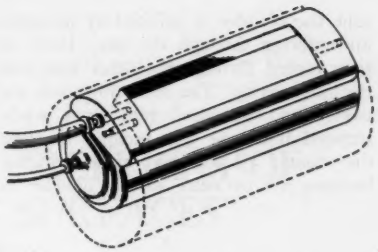


FIGURE 5.

practical to inspect by the rigid replica method described. For larger sections it appears entirely feasible to locate a dam or mold inside a pipe at a desired area and to cast a thermosetting resin into the mold.

A suggested mold (5) is shown in Figs. 5 and 6. Fig. 5 is a perspective view of an uninflated mold designed for taking a plastic impression inside a tube. Fig. 6 is a longitudinal section through this mold after inflation in the tube and it shows the plastic after it is forced into the casting area. The dotted lines in Fig. 5 show the position of the device after it is inflated.

The device consists of an inflatable bladder to which is secured a flexible mold. The two comprise the complete dam. The device is positioned in a tube by the operator pushing on the air line. After reaching the proper position in the

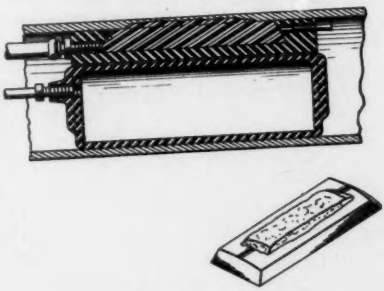


FIGURE 6.

tube the bladder is inflated by pressure air entering through the line. Resin is then forced through the other line into the mold cavity. The resin flows into the cavity and damaged tube area while trapped liquid or gas escapes through the vents. When the resin casting hardens air pressure in the bladder is released. The device is thus reduced in diameter and may then be withdrawn from the tube. The resin casting can then be easily removed from the flexible mold. The casting is an accurate three dimensional replica, rigid and suitable for handling, of the damaged tube area.

CONCLUSIONS

Several possible applications of a thermosetting resin to record surface roughness of areas submerged in water or oil (only SAE 30 has been tried) have been suggested. It is hoped that these suggestions may be of value to those who may be confronted with the problem of determining wear, surface roughness or corrosion of areas submerged in liquids.

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COMMENTS ON "REPLICAS OF SUBMERGED SURFACES"

JOHN W. SAWYER

LYNDON CRAWFORD, *Chief Analytical Engineering Dept., Reed Research, Inc. Washington, D. C.*

As a Naval architect it is interesting for me to see that devices for preparing replica surfaces of submerged objects are practicable. Full size measured mile tests are a necessary part of the research on ship form and other characteristics and in promoting better model-to-ship predictions as well as in qualifying the vessels themselves. Comparative roughnesses of various vessels are an important ingredient in the analysis of data but differences are often relatively small. Because of this, the doubt as to the exact condition of the ship's bottom *on the day of the ship's trial* is a considerable handicap, but obviously a ship cannot be docked every trial day. Therefore, if some means of sampling such replica data were available, I believe much of this doubt could be removed, and in some cases data of doubtful validity could be readily removed from further consideration. Furthermore, this kind of technique might be very useful over longer periods in understanding the thorny but important problem on effective marine growth and extended power predictions for vessels some time out of dry dock.

Another possible marine application occurs to me regarding cavitation damage. Certain underwater objects, even non-rotating objects, have pitted in very short intervals of time. Docking again for frequent examination is not practicable, but a diver's report on the condition of such objects is likely to be vague. Here again a technique of obtaining exact replicas would be exceedingly useful and, if repeated systematically, could provide a rather good time record on cavitation damage.

REGULATORS FOR THE MARINE INDUSTRY

ACKNOWLEDGMENT

This article appeared in the July 1953 issue of "Westinghouse Engineer." It was written by MR. S. A. HAVERSTICK.

The application of automatic regulating systems to ships offers as much, if not more, variety than is found in industrial installations. Within the hull of a modern passenger or fighting ship are contained regulators for accomplishing a myriad of tasks. While many of these applications are, for security reasons, classified, some can be discussed.

VOLTAGE REGULATORS

Probably the most important type of automatic regulator found in the marine industry is the voltage regulator used for auxiliary power systems. Every ship of any consequence has an auxiliary power system for ship's service. The generating plant for these systems may be as much as 12,000 kw for one of the Navy's large aircraft carriers. The voltage must be regulated within relatively close limits.

An example of modern voltage-regulating methods in the marine industry is the type WRN-11 voltage regulator. This regulator has found wide use in the Navy for ship's service generators varying in size from 60 to 1500 kw. It is of the rotary-amplifier type and consists of (1) a Rototrol exciter directly connected to the generator and (2) a static electrical measuring circuit. It is shown diagrammatically in Fig. 1. The output voltage of the generator is fed through a static measuring circuit whose output is a d-c potential that varies in polarity, according to a high or low condition of the generator voltage, to energize the control field of the Rototrol exciter. The terminal voltage of the exciter is regulated by this low-energy controlled field to effect the required change in the generator excitation and consequently the generator output voltage. Physically, the equipment involved in the WRN-11 regulator consists primarily of an automatic-control unit and a so-called potential unit, together with a manual-control unit (not shown in the figure), a voltage-adjusting rheostat, and a current transformer. The potential unit is energized by the a-c generator voltage and current. Its output is a single-phase a-c voltage that is used to energize the automatic-control unit through the voltage-adjusting rheostat. This automatic-control unit is a voltage-sensitive device, the output of which is a d-c

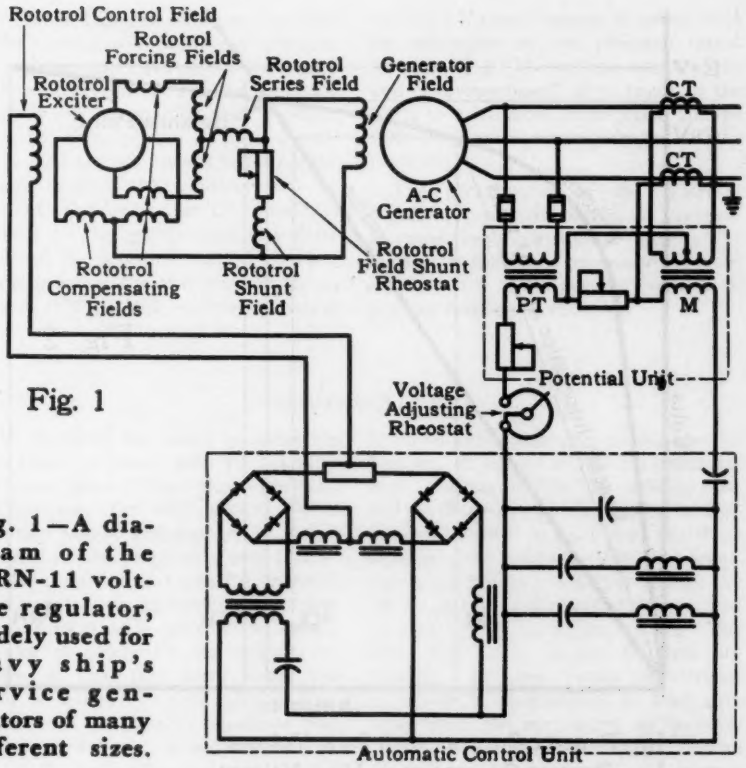
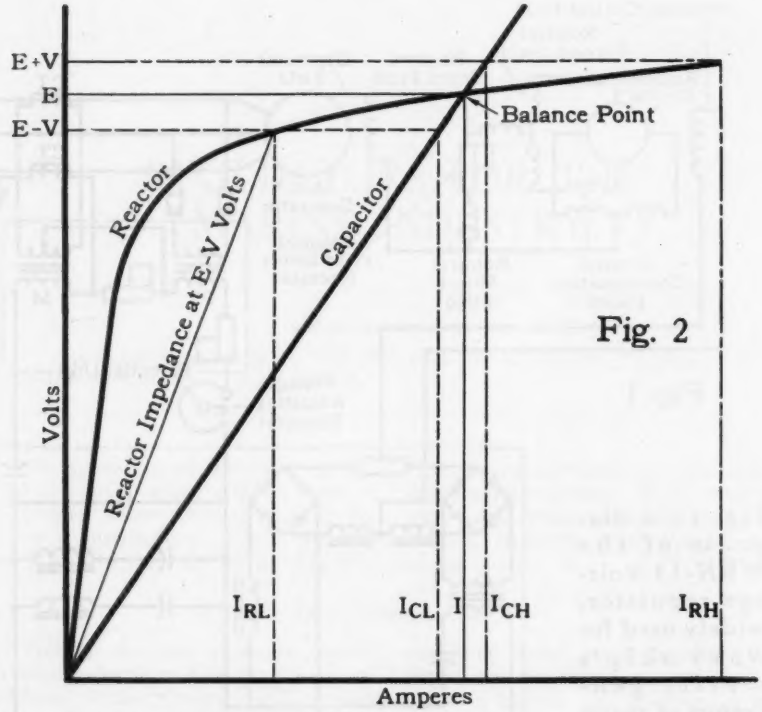


Fig. 1

Fig. 1—A diagram of the WRN-11 voltage regulator, widely used for Navy ship's service generators of many different sizes.

voltage; this output is then impressed upon the Rototrol exciter control field. When the generator output voltage is at the desired value, the output voltage of the automatic-control unit is zero. If the generator a-c output voltage increases above the regulated value, the d-c output voltage of the regulator will be in the direction to decrease excitation voltage through the Rototrol exciter. When generator voltage falls below regulated value, the opposite is true.

The voltage-sensitive device consists of two parallel circuits, one containing a capacitor and the other a saturating reactor. The volt-ampere characteristics of these two elements are shown in Fig. 2. The point where the two curves intersect is the balance point of the two impedances. The operation of the voltage regulator depends on the fact that, if the voltage increases above this point, the current through the reactor is greater than that through the capacitor. When the voltage decreases below the balance point, the capacitor current is greater. When any unbalance occurs, a current flows in the Rototrol control field. Since the voltage-sensitive circuit consists of elements responsive to frequency, some means of frequency compensation must be provided; this is introduced in the WRN-11 regulator by



I_{RL}=Reactor Current with Low Voltage
I_{RH}=Reactor Current with High Voltage
I_{CL}=Capacitor Current with Low Voltage
I_{CH}=Capacitor Current with High Voltage
I=Reactor or Capacitor Current at Normal or *E* A-C Line Volts

Fig. 2—Volt-ampere characteristics of the capacitor and reactor circuits for the WRN-11's voltage-sensitive device.

a circuit between the generator and the voltage-sensitive circuit. The effect of an increase in frequency when the voltage-sensitive circuit is operating at the balance point is to increase the current in the capacitor branch and decrease that in the reactor branch. This causes control current to flow in the "raise" direction, which is the same effect that would be obtained by a decrease in voltage. In order to compensate for this effect, the voltage across the voltage-sensitive circuit must be increased as the frequency increases, or, conversely, it must be decreased as the frequency is decreased below normal. This response is obtained by means of a series condenser of the proper value

such that it, together with the reactance of the circuit, will accurately compensate for frequency variation. The automatic-control unit used in the regulator responds to a single-phase voltage. Since the three phases of the a-c generator load are not always balanced, the voltage drop in the windings may be different. Correction for this condition is made by the positive-sequence filter circuit of the potential unit. This filter circuit involves the two current transformers *(CT)*, which energize a mutual reactor *(M)* and resistor in series with the secondary of the potential transformer *(PT)*. The voltage output of the unit is proportional, as a result of the filter, to a balanced three-phase voltage (the positive-sequence voltage) of the machine.

The performance of the WRN-11 regulator is approximately ± 1-percent at rated frequency and at unity power factor. Its frequency compensation holds voltage with ± 1.5 percent for a ± 5-percent frequency variation.

STABILITY REGULATOR

The Rototrol has found considerable application on board ship for stability regulation of a-c turbine-electric propulsion systems. On such drives, where minimum weight and size are essential, the synchronous propulsion motor driving the propeller is normally operated very near to its pull-out torque, and some means must be provided to insure a factor of safety for the sudden increases in load that occur when the vessel is maneuvering or operating in a rough sea. A stability regulator that controls excitation as a continuous function of the load uses a combination of current and line voltage to measure the load. While it would be possible to use a direct rheostatic type of control element, it has been found more expedient to use a rotary amplifier to control the exciter. This method of control eliminates the mechanical parts inherent with a rheostatic regulator, and substitutes a Rototrol with its associated electrical circuits.

The stability regulator must be able to follow load fluctuations as rapidly as they occur and maintain the field current on the propulsion motor and generator at a sufficiently high value to prevent pull-out. The circuit must be stable at all times and have no tendency to cause self-sustaining oscillations or hunting. A circuit of this type that has been used successfully for stability control is illustrated schematically in Fig. 3. The Rototrol in the circuit has three separate field windings. The first winding is excited by a constant-voltage d-c source that fixes the normal polarity and voltage of the excitation circuit. The other two fields on the Rototrol are variable. The field acting to increase excitation is proportional to load current, while the one acting to decrease excitation is proportional to the voltage divided by the frequency. At normal values of load, the two variable fields on the Rototrol are nearly equal and opposed so that the generator flux is produced chiefly by the constant-strength field. When the load increases, the propulsion-motor current rises and the voltage tends to decrease. Both of these effects, then, tend to increase the output of the exciter and raise the field current to carry the increased load. If the load falls off, the effects are exactly the opposite and the field current decreases. Rectifiers are provided in the regulating field circuits so that a d-c field is produced that is proportional to the alternating current in the propulsion circuit. The "volts per cycle" characteristic is obtained by using a reactor in

the a-c circuit, as indicated in the schematic diagram. When the reaction of the circuit is high compared with the resistance of the circuit, the current will be proportional to the voltage and inversely proportional to the frequency.

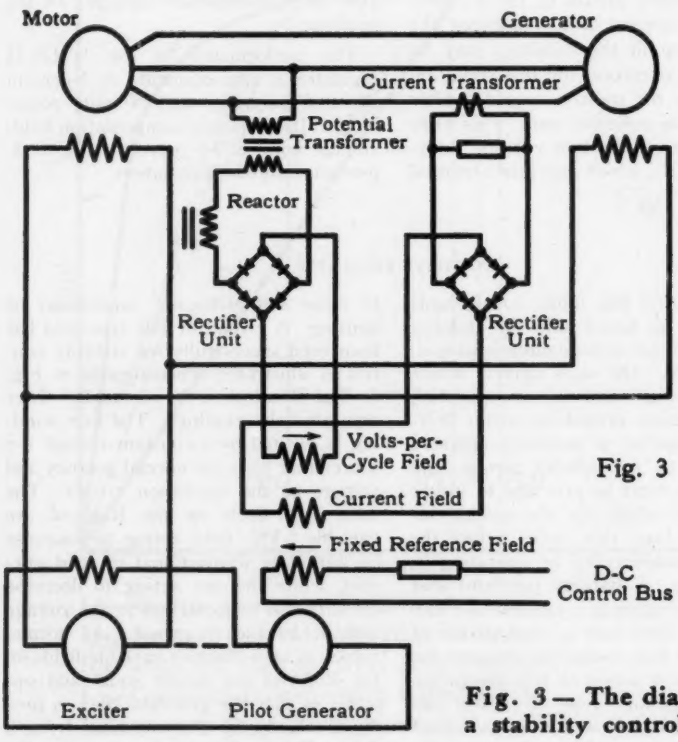


Fig. 3

Fig. 3 — The diagram for a stability control circuit.

POSITIONING REGULATORS

A rather unusual regulator application for a marine installation was made on the seagoing hopper dredge *Essayons,* operated by the U. S. Army Corps of Engineers. A hopper-type dredge is a vessel whose function is to collect mud and silt from the bottom of harbor channels, and carry it out to sea where it can be dumped. The press has referred to these dredges as "seagoing vacuum cleaners." Silt and mud are sucked from the floor of the harbor by a long length of pipe called the "drag pipe," which is suspended over the side of the vessel. The mixture of mud, silt, and water is pumped into large hoppers on board the dredge. There the mud and silt settle out and

the water is allowed to flow overboard. Once the hoppers are filled, the dredge puts out to sea where the mud is dumped through trap doors in the hoppers.

The drag pipe requires a very complicated hoisting system. The depth of the drag head must be changed frequently in accordance with the contour of the bottom of the harbor being dredged. For this application three winches are used to position the drag pipe. It is necessary that the winch drums maintain a fixed position with respect to each other in order that stresses are not set up in the drag pipe or that excessive rotation around the ball joint does not damage it. The speed of each hoist motor is controlled by varying the field of a single variable-voltage exciter, which simultaneously supplies field current to the three drag-hoist generators—one for each hoist motor. To maintain proper synchronism, two of the generator fields have Rototrol exciters that add or subtract from the respective generator voltages as the trunnion-and-ball-joint hoist motors tend to lead or lag the drag-head hoist motor as a reference. This automatic control is accomplished by means of rheostats that are geared to the winches themselves and are connected in a group of bridge circuits, as shown in Fig. 4. The unbalance of any bridge applies corrective field to the respective Rototrol exciter. During normal dredging operation only the drag-head and ball-joint winches are used and the drag pipe rotates around the trunnion as a pivot. For this operation, limit switches are used to remove the trunnion motor from the system. All three motors function, however, when the drag pipe is raised above the water line for stowing on deck.

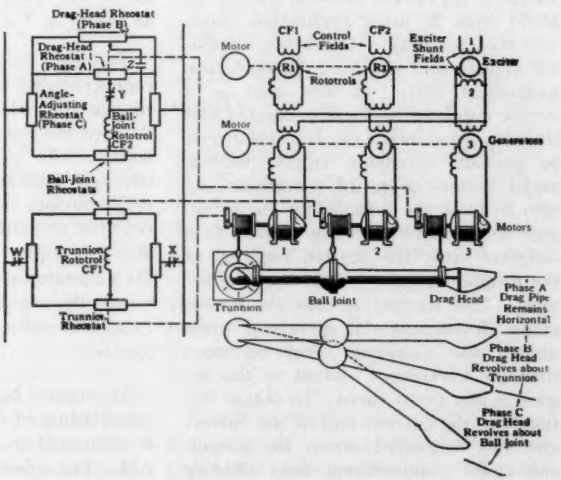
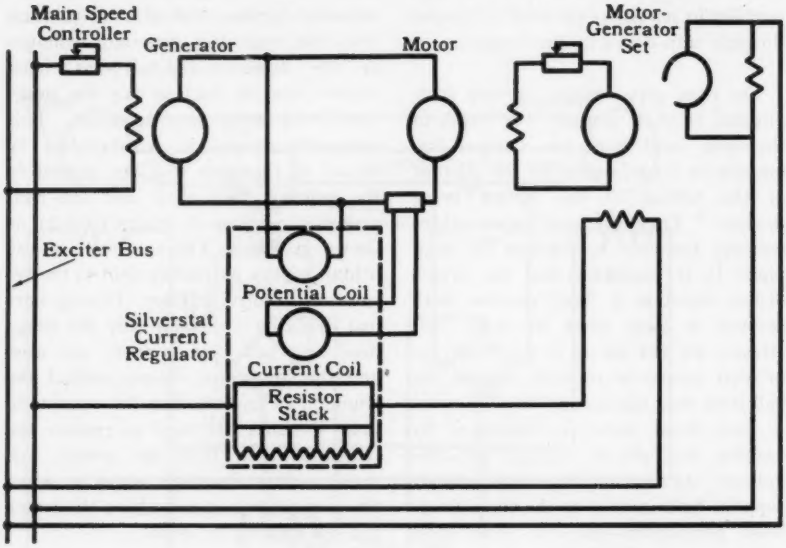


Fig. 4—A schematic diagram of the position-regulator system for the dredge drag pipe. For *Phase A* operation, contactors *W*, *X*, and *Y* are closed, and contactor *Z* is open. For *Phase B* operation, contactors *W*, *X*, and *Y* are open and contactor *Z* is closed. *Phase C* is accomplished by the angle-adjusting rheostat, with the contactors set for *Phase B* operation.

Fig. 5—Diagram of a Silverstat regulator used to regulate torque.



LOAD REGULATOR

Sometimes a standard regulator can handle a regulation problem that is far afield from its usual application. Such was the case with a Silverstate regulator applied to a small d-c diesel-electric propulsion drive. It was used as a torque regulator and was connected into the propulsion-motor exciter-field circuit to provide maximum engine loading under various operating conditions, and also to limit the load on the diesel engine to its nominal rating. Stated in a different way, the desired function of the torque regulator was to regulate the motor field current so that the motor, under all conditions of operation, would absorb the maximum (but no more than the maximum) output of the engine at any given speed. To obtain this function, the current coil of the Silverstat was connected across the propulsion-motor commutating field winding and the potential coil was connected across the propulsion motor armature as shown in Fig. 5.

The two coils are so designed and connected that the ampere-turns of the current coil, which predominate, oppose those of the potential coil. As the regulator is set to operate on a predetermined total number of ampere-turns, it is obvious that the motor current required to actuate the regulator is reduced as engine speed, and consequently the generator voltage, is reduced. As a result, the regulated motor current decreases in value as the engine speed is lowered.

To reduce hunting of the regulator, one winding of the damping transformer is connected in series with the current coil. The other winding is connected

from the center tap of the motor-field discharge resistor to either the positive or the negative side of the field through a directional relay. This relay is so arranged that it will reverse its contacts on reversal of polarity of the generator field. In this way, the damping transformer is of proper polarity for both the ahead and astern operating conditions. Any change in the field voltage caused by action of the regulator induces a voltage in the transformer secondary. A change in the field current opposes a change in the regulator-coil current and therefore anticipates the change in the motor-field current, and consequently in the armature current, before it actually has been completed. This reduces overregulation and hunting. To reduce hunting still further, a dashpot was attached to the regulator armature lever.

During constant-operation conditions, the horsepower developed by the propeller varies approximately with the cube of the speed. If conditions change, however, and the resistance to the movement of the ship is increased, as would be the case if the ship picked up a tow, the power needed for any given speed is increased. If the ship were originally running at 100-percent speed and if no changes were made in the control, the motor would continue to operate at 100-percent speed and would simply try to draw more current to develop the increased torque imposed by the load. Such an overload condition is not desirable for the diesel engine, which ordinarily is not capable of withstanding any appreciable overload. The engine would stall unless the motor field were increased. Increasing the motor field slows down the motor to a point where the same horsepower is developed but at increased torque and decreased speed. This is the duty of the automatic torque regulator.

ELECTRONIC REGULATOR

Many electronic regulators have been applied in the marine industry. A simple, but interesting application is the electronic governor for a ship's service turbine-generator set. Electronic governors have the advantage of combining the high degree of sensitivity obtainable from electronic devices with the low-inertia, high-force characteristic of a hydraulic servomechanism. Because an electronic governor is electrically connected to the system, it does not have to be located physically at the turbine as would be the case with a mechanical governor.

This electronic governor was designed to give a maximum performance of one half of one-percent speed regulation during nonparallel operation of the unit. Maximum stability and transient response are obtained by using an anticipation network and a circuit that detects rapid rates of load change. The anticipation circuit introduces a signal proportional to the first derivative of the error signal. Essentially, it is a lead network that tends to compensate for lags occurring elsewhere in the system. The anticipation circuit aids both stability and transient response. The rate of load-circuit change aids only response. Since the usual governor responds to a change in speed, it can only detect a change in load by the speed change that results. It must wait for this change in speed before corrective action can be initiated. This delay is detrimental to good transient response. On the electronic governor it is relatively easy to introduce a voltage proportional to the rate of change of load, in such a way as to correct for a change in speed almost before the change occurs.

Many electronic regulating systems are presently undergoing considerable redesign to accommodate magnetic am-

plifiers. The rebirth of the magnetic amplifier as distinguished from the saturable reactor is generally credited to the Germans, who prior to and during World War II developed countless applications for its use. By far the majority of these applications were in the marine and aviation fields. The German Navy used the device in its gun stabilizers and the Luftwaffe applied it to automatic pilots and ground-approach systems.

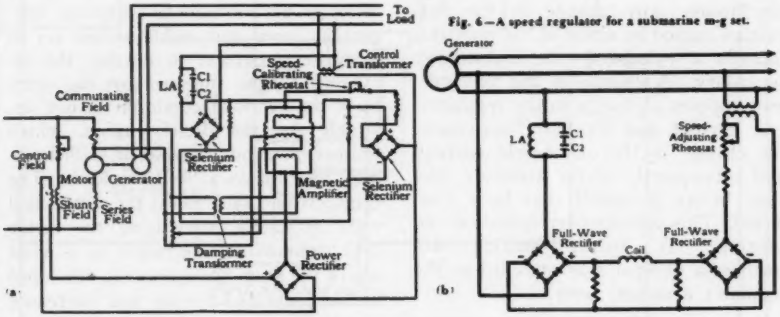


Fig. 6—A speed regulator for a submarine m-g set.

MAGNETIC-AMPLIFIER REGULATORS

Submarines now in service depend on diesel engines for their prime source of power. This power is converted into electrical energy for propulsion; a storage battery of considerable size acts as a reservoir for the electrical energy generated. This permits continued operation of the propulsion motors when the submarine is submerged below snorkel depth and the diesels are shut down. The ship's service power system on such craft is superimposed on the battery system. Direct-current auxiliary loads are supplied directly, while a-c loads receive power through d-c to a-c motor-generator sets. Unfortunately, the battery, depending on the condition of its charge, may have a voltage anywhere between 450 and 710 volts. Since many of the a-c loads on the submarine must have a constant frequency as well as constant-voltage supply, it is necessary to provide rather involved speed and voltage regulators for the m-g sets. The speed regulator for such an m-g set is shown in Fig. 6a. The input-control transformer receives single-phase power at 450 volts from the generator and steps it down to 225 volts for the regulator circuits. The magnetic amplifier (see Fig. 6a) provides a means whereby relatively small control signals derived from the frequency- and voltage-reference circuits can control a relatively large current applied to the control-field coils of the motor. The parallel resonant circuit and the signal-voltage rectifier, together with the reference-voltage rectifier, furnish the principal control signals to the magnetic amplifier.

Power from the control transformer is applied to a frequency-sensitive network and to the magnetic amplifier. The output of this amplifier is applied to the main rectifier, where it is converted to direct current and then applied to the motor control field. The frequency-sensitive circuit (see Fig. 6b)

consists of a bridge network, of which one leg is composed of the automatic speed-calibrating rheostat and a fixed resistance in series with a full-wave selenium rectifier. This leg is energized from the secondary of the control transformer. The other leg consists of a parallel resonant circuit (formed by a reactor and capacitors) in series with a similar full-wave rectifier. The resistive-leg output is a d-c voltage, used as a reference. The resonant-leg output is the regulating voltage.

These are but a few of the regulators found in the marine industry. There are many, many more. However, the examples outlined here serve as a graphic illustration of the variety of automatic regulating systems found on modern ships.

LARGE DRY DOCKS

ACKNOWLEDGMENT

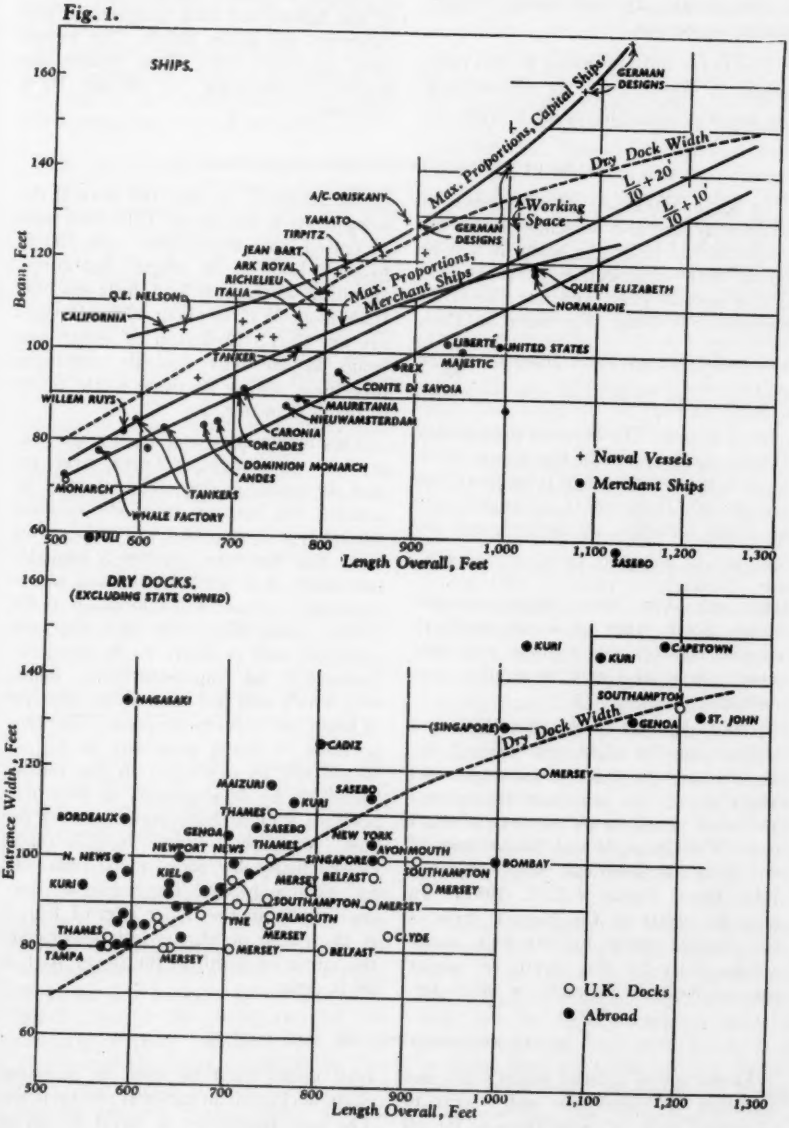
This article is an abridged version of a paper presented at the Spring Meeting of the Institution of Naval Architects, in London, 25 to 27 March, 1953. The author is E. LESLIE CHAMPNESS, and the article was published in the 15 May issue of "Engineering".

The two large dry docks at Sydney and Capetown were discussed in papers read before the Institution of Civil Engineers early in 1948, following which a special Dry Docks Committee, under the chairmanship of Mr. M. G. J. McHaffie, was initiated by that Institution, charged with reviewing the design and equipment of dry docks. By request, the Institution of Naval Architects appointed two representatives—Mr. G. McL. Paterson and the present author—to represent the naval architectural point of view, and to give assistance on the main committee and on various panels, together with many experts experienced in civil engineering and mechanical equipment connected with dry docks, cranes, pumps, etc. The results of their deliberations were published by the Institution of Civil Engineers in 1952 as *Dry Docks—Memorandum on Construction and Equipment.*

The Admiralty point of view was taken care of by direct representation on this committee of the Director of Naval Construction and the Dockyard and Civil Engineering Departments; their requirements and resources differ to some extent from those of private docks, though inevitably, in times of emergency, the Admiralty becomes a major user of private facilities. No doubt this *Memorandum* will be studied in detail by those contemplating building new dry docks and by the various experts who carry out such projects. At any rate, the numerous headings of almost everything concerned, and the merits or demerits of alternative equipment, were very fully discussed, though little of this appears in the *Memorandum,* which, under the terms of reference, restricts itself to summarizing the conclusions reached.

Not all of this is much more than of general interest to those who are the users of dry docks, who are chiefly concerned in getting the most efficient service they can, nor to all dry-dock owners, though much of it will amply repay study by them; and if they are private dry-dock owners they will doubtless weigh up the commercial return or necessity for all the items dealt with in this comprehensive survey. Much depends on the demand and type of work undertaken by particular private establishments, and the diversity and incidence of this colors the individual requirements and necessities of private firms. Opinions and experience naturally vary, but almost all aspects are covered by this *Memorandum* and much

Fig. 1.


SHIPS.
Beam, Feet
Length Overall, Feet
Max. Proportions, Capital Ships
Dry Dock Width
L/10 + 20
Working Space
L/10 + 10
Max. Proportions, Merchant Ships
GERMAN DESIGNS
A/C ORISKANY
YAMATO
TIRPITZ
JEAN BART
ARK ROYAL
RICHELIEU
ITALIA
Q.E. NELSON
CALIFORNIA
QUEEN ELIZABETH
NORMANDIE
TANKER
LIBERTÉ
UNITED STATES
MAJESTIC
REX
CONTE DI SAVOIA
WILLEM RUYS
MAURETANIA
NIEUWAMSTERDAM
CARONIA
ORCADES
DOMINION MONARCH
ANDES
MONARCH
TANKERS
WHALE FACTORY
PULI
ASEBO
+ Naval Vessels
● Merchant Ships
DRY DOCKS,
(EXCLUDING STATE OWNED)
Entrance Width, Feet
Length Overall, Feet
Dry Dock Width
KURI
CAPETOWN
NAGASAKI
SOUTHAMPTON
(SINGAPORE)
GENOA
ST. JOHN
CADIZ
MERSEY
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BORDEAUX
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THAMES
AVONMOUTH
SINGAPORE
BOMBAY
KIEL
BELFAST
SOUTHAMPTON
MERSEY
SOUTHAMPTON
MERSEY
TYNE
FALMOUTH
MERSEY
CLYDE
THAMES
TAMPA
MERSEY
MERSEY
BELFAST
○ U.K. Docks
● Abroad

valuable information is at the disposal of the private dry-dock owner contemplating expansion.

The notes initially given to this committee in April, 1948, as representing the naval-architecture point of view, on the particular questions of proportions of length to beam, naval requirements of the future and dock proportions and facilities, are given below. No events have occurred since then, within the author's knowledge, to change these opinions.

TREND OF PROPORTIONS OF LENGTH TO BEAM

In an examination of a number of large merchant and passenger liners for proportion of length to beam, it will be found that—irrespective of their particular service (i.e., Atlantic, Pacific or Europe—Far East, via Suez or Panama), they range from Beam $= \frac{L}{10} +$ 5 ft. to $\frac{L}{10} + 21$ ft., where L = length overall in feet. The beam of present-day vessels tends towards the upper limit. Certain special classes of large merchant vessels, 500 ft. to 700 ft. in length, such as whale factories, oil tankers, and ore vessels, are generally of the $\frac{L}{10} + 20$ ft. type, and some have slightly greater beam. Some types of naval auxiliary vessels, such as depot ships and fleet repair ships, also rise to similar proportions.

From the purely naval-architecture design point of view, the natural expansion over the years of passenger and cargo vessels for minimum transportation costs would be by increase of draft (see "The Draught and Dimensions of the Most Economical Ship," by Sir John Biles, *Trans. I.N.A.*, 1931). In fact, the draft of the largest ships is still limited more by dry-dock availability than by the depth of major canals, dredged channels or other terminal facilities, so that the normal developments in the period 1910-1948 have increased liner dimensions from 700 ft. to over 1,000 ft. in length; but corresponding increase in load draft has only risen from 35 ft. to about 40 ft. Designers are thus still driven to length and beam as the only possible expansion directions, owing to these world limits of depth of water.

This tendency to increased beam proportions in passenger liners, over the past 40 years, is due chiefly to the increased top hamper from the original modest type to present luxury types, and, since this has now reached a probable maximum, it is unlikely that any corresponding increase will take place in the future. Light-alloy material is also now available and is likely to be used increasingly for superstructures, boats, etc., which will not necessitate increase of beam for stability purposes. The proportions of docks proposed in Fig. 1 should not be overtaken in the future, therefore, by developments in ship proportions such as have occurred over the past 40 years, which have already caused many dry docks to be relatively too narrow today. The curve of dry-dock width in the upper part of Fig. 1 is the curve of ideal width suggested; the curve of width in the lower part is 10 ft. less.

NAVAL REQUIREMENTS OF THE FUTURE

As the age of assured world peace and abolition of armaments still seems to be a long way off, requirements for all dry docks must still take cognizance of naval requirements, since, as always, civil docks must be used in assisting State dockyards in national emergencies. The past tendencies in naval design in the pre-atomic period, up to 1944, show the same trend as for all other vessels,

namely, steady and progressive increase in size, though generally with extreme beam characteristics. The largest key vessels setting the pace for dry docks (or perhaps more correctly, of which the dimensions have been limited by existing or projected dry docks) were battleships and aircraft carriers.

The latest published information as to the tendency and size of battleships in the pre-atomic era is probably that given by Commodore Schade, USN (*Trans. Soc. of Mar. Eng. and Naval Arch.*, New York, 1946) on "German Wartime Technical Developments." This quotes the developments of the German "H" type of battleship, one of which was laid down by Blohm and Voss at Hamburg in 1939 but was never completed. The design was under continuous review on paper by the German naval authorities and increase in size and proportions was made as follows:—

Length	Beam	Draft	Date
Ft.	Ft.	Ft. in.	
910	122	33 0	1939 as laid down
902	128	40 0	— as laid down— "H" '41 design
1,000	141	—	1942 "H" '42 design
1,082	158	42 3	1942 "H" design
1,132	169	44 3	1944 "H" design

For these vessels, Germany constructed three dry docks at Hamburg, Bremen, and Wilhelmshaven—now all destroyed—which were 1020 ft. to 1140 ft. by 197 ft.

As far as very large capital ships with normal pre-atom armament are concerned, the tendency appears to be for beam proportions to extend very rapidly, requiring dry docks of extreme breadth, which would be uneconomical for ordinary normal requirements. These vessels and the large capital ships (see Dr. Oscar Parkes, *Trans. I.N.A.*, 1949) and the present United States aircraft carrier policy represent so far the upper limits.

There is as yet no information, nor any actual building of new vessels, which indicate the probable tendencies of naval construction embodying the results of the observations of the 1946 Bikini and later atomic bomb experiments or radar developments, except in smaller craft for submarine detection and offense. General naval and technical opinion indicates that the existence of such weapons, though they may change the character of naval fighting units, will not see the end of sea-borne navies, either for offense or commerce protection. The atomic bomb, and other offensive weapons developed from it, in conjunction with rocket or jet-propelled direct or guided missiles will alter considerably the offensive weapons carried and the type of protection required against them.

This protection, both against blast, heat, and under-water bursts, would seem to indicate that size would develop in much the same manner as with existing conventional weapons of the past. Indeed, the tendency to present a small surface, under and above water, to shock transmission may limit draft and increase beam in much the same manner as at present. It may well be, however, that the fleet of the future may consist of smaller units, more readily dispersable and, except for action, not necessarily to be habitable in the manner of the past and present naval vessel. Personnel may be borne normally in fast mobile parent vessels, similarly dispersable, the size and type of which are as yet undeveloped.

Since this matter of naval tendencies concern only the docking facilities for very large types of capital ships, and such large projects as super dry docks will not be lightly entered upon in present days of high cost levels, it is probable that the trend will be clearer before any such enterprise is begun. Whatever the size or proportion of a dry dock, the position eventually arises where it docks a "shoe-horn" case of

the maximum size of vessel which it can accommodate. If this case happens to be an aircraft carrier of the present relatively standardized type—that is, with offset bridge structure and gun sponsons clear of the flying deck— these projections, both in the state of high water level when docking and at the level docked down on the blocks, indicate the desirability of dock-side crane structures, high lighting standards, etc., being kept approximately 25 ft. clear of the maximum beam line, though this necessarily increases the length of any crane jibs which are required to be able to plumb the center of the dock.

SUGGESTED DOCK PROPORTIONS

The upper part of Fig. 1 indicates the proportion of a number of past and present large merchant and war vessels, with enveloping curves of maximum proportion of length to beam. From the merchant-ship point of view, this gives rise to a curve of dry-dock width on a basis of length overall allowing suitable clearance for repairs. Vessels of smaller length, with out-of-proportion beam, can generally be accommodated in dry docks (of which there are probably a large number) up to 100 ft. longer than the vessel itself, and this applies to vessels such as naval monitors and Maracaibo types of oil tankers.

The lower part of Fig. 1, on the same basis, indicates the overall length and average entrance width of large docks in this country and abroad. The fact that all but about six of the existing United Kingdom mercantile dry docks lie below the line of ideal entrance width for present-day lengths, whereas over 50 dry docks abroad, apart from floating docks, lie above this curve, indicates the extent to which many United Kingdom docks are now out-of-proportion with modern trends.

The extent of modern services necessary, and provided in many cases in those large private dry docks which cater for long-term repair jobs, and frequently call for maintenance of officers and crew living on board, are not always realized—particularly when compared with many public dry docks, which are mainly occupied by quick turn-round jobs, painting, etc., and stern-gear work only, as happens in some terminal ports. These services may be listed shortly, apart from the shops which serve every shipyard trade, as:—

Pumping and drainage.

Cranage—dockside—for quick light lifts and slower heavy machinery at large radius, reaching the centerline of wide docks.

Salt water; fire, tank-testing, magazine-flooding.

Fresh water; ship supplies, wet sand-blasting, sprinkler system coupling.

Frost precautions to water systems.

Compressed air; working tools; sand or grit blasting; plastic painting, hot and cold.

Sewage disposal (occupied ships); sewage mains and branch connections.

Shore facilities; canteen and galley; sanitary and wash places; fire patrols.

Telephones—for use of personnel remaining on board; fire alarms, etc.

Electric light and power; domestic use, light, heat, etc.; working tools, welding, floodlighting dock area and in dock; temporary leads.

Steam: heating, coupling to ships fire pumps; sand-blasting, oil and sludge heating.

Oxy-acetylene mains; burning away.

Oil-fuel storage and settling tanks; transfer line; sludge disposal.

Lifts to dock bottom; personnel and material.

TABLE I.—NUMBER OF DOCKS AVAILABLE.

Entrance width	Dry Docks.			Floating Docks.			Total.		
	80 ft. and over.	90 ft. and over.	100 ft. and over.	80 ft. and over.	90 ft. and over.	100 ft. and over.	80 ft. and over.	90 ft. and over.	100 ft. and over.
Mercantile dry docks :									
Public and private—									
U.S.A.—									
Atlantic	8	4	1	38	18	4	46	22	5
Pacific	7	1	1	18	13	1	25	14	2
Total	15	5	2	56	31	5	71	36	7
Great Britain—									
Public	15	10	6	—	—	—	—	—	—
Private	10	3	—	—	—	—	25	13	6
Total	25	13	6	—	—	—	25	13	6
South Africa	3	2	2	—	—	—	3	2	2
Canada—									
Atlantic	1	1	1	2	2	2	3	3	3
Pacific	—	—	—	3	3	1	3	3	1
Australia and New Zealand	2	—	—	1	—	—	3	—	—
Other Commonwealth	3	2	1	—	—	—	3	2	1
Japan	20	17	9	1	—	—	21	17	9
Italy	5	5	3	—	—	—	5	5	3
Holland	1	—	—	8	6	4	9	6	4
Germany	5	2	—	4	3	2	9	5	2
France	5	4	3	4	—	—	9	4	3
Sweden	3	—	—	5	1	—	8	1	—
Belgium	3	1	—	—	—	—	3	1	—
Spain	3	2	1	—	—	—	3	2	1
Other countries	8	1	1	3	3	3	11	4	4
Total	102	55	29	87	49	17	189	104	46
State-owned dry docks :									
U.S.A.—									
Atlantic	19	16	10	—	—	—	19	16	10
Pacific	20	17	12	1	—	—	21	17	12
Total	39	33	22	1	—	—	40	33	22
Great Britain—									
Home dockyards	14	12	8	1	1	1	15	13	9
Foreign and Commonwealth	13	11	5	3	2	2	16	13	7
Total	27	23	13	4	3	3	31	26	16
France and Colonies	18	16	11	—	—	—	18	16	11
Italy	6	6	5	2	2	1	8	8	6
U.S.S.R.	4	3	1	1	1	1	5	4	2
Other countries	5	4	3	1	1	1	6	5	4
Total State	99	85	55	9	7	6	108	92	61
Total public and private	102	55	29	87	49	17	189	104	46
World total all docks	201	140	84	96	56	23	297	196	107

TABLE II.—WORLD TONNAGE: 30 YEARS' INCREASE IN BEAM (MERCANTILE PASSENGER OR CARGO VESSELS AND TANKERS.)

—	Gross Tonnage, Over 70 Ft. Beam.	Number of Vessels 70 Ft. Beam and Over.	Number of Vessels.			
			Over 70 Ft. Beam and Under 80 Ft.	Over 80 Ft. Beam and Under 90 Ft.	Over 90 Ft. Beam and Under 100 Ft.	100 Ft. Beam and Over.
1924*	1,579,502	80	70	5	3	2
1952 (October)*	7,973,739	510	376	123	7	4
1954 (estimated)	9,750,000	663	500	150	9	4

* By courtesy of Lloyd's Register of Shipping.

Extensive staging; trestles, blocking, shoring and supporting gear for damaged structures, keel-block cradles and storage for same.

Handling gear; capstans, bollards, fairleads, leading-in gear, etc.; diesel tractor tugs for block line adjustment work in dock bottoms, etc.

Hydraulic power.

Modern repair facilities require in addition ample quay spaces similarly equipped for work afloat, which are, in fact, practically one-sided docks. Vessels drawing as much as 42 ft. of water afloat, damaged from war causes, or loaded ships, may also occasionally be accommodated. The thickness of dock bottom is an important factor in these cases and for other repair cases of special loading.

THE CALCULATION OF NON-LUMINOUS RADIATION IN CONVECTION TUBE BANKS

IRVING GRANET

THE AUTHOR

Born July 2, 1924, in Brooklyn. Attended Brooklyn Technical High School and received Bachelor of Mechanical Engineering Degree from Cooper Union in 1944. Served two years with Air Corps overseas as Flight Engineer. Employed 1944-45 on Navy Torpedo project as project engineer on stress and vibration studies. Since 1947, employed as project engineer, Research Department, Foster Wheeler Corporation. In June 1948 received Master of Mechanical Engineering Degree from Polytechnic Institute of Brooklyn and in 1949 received Professional Engineers License in New York. At present going to Brooklyn Poly for Doctorate degree and also teaching Thermodynamics in the evening session. Has published several articles on properties of gases.

In a previous article (1) the author has shown that radiant heat absorption can be calculated in furnaces on a rational basis. The method used was essentially an application of the well known Stefan-Boltzmann Equation (4) with the proper consideration of those factors by which it must be modified when used to calculate furnace heat absorptions. When burning solid or liquid fuels the flames will be found to be luminous due primarily to soot formation, dust or particles of powdered coal. Once the products of combustion have left the furnace and have passed the second row of the screen tubes (as is the usual case in most furnaces) this type of radiation is no longer of importance and gas mass transfers heat to the receiving walls by a form of radiation often termed to be non-luminous. This transfer (and absorption) of heat occurs in the infra-red spectrum. In the calculation of heat transfer in convection sections especially at high gas temperatures it is necessary and essential that this type of radiation be accounted for in addition to the convection heat transfer.

It was at the beginning of the present century that this type of radiation was first demonstrated to be thermal in character. Of the common gases important industrially, water vapor, carbon dioxide, carbon monoxide, sulfur dioxide, ammonia and hydrocarbon

vapors are among the strongest radiators and absorbers. Gases such as nitrogen are capable of transmitting this infra-red radiation without either absorbing or emitting it in any appreciable amounts. Of the gases that emit and absorb, the ones that emit and absorb in the greatest amounts when hydrocarbons are burned are carbon dioxide and water vapor (for complete combustion with a negligible amount of sulfur dioxide formed from sulfur in the fuel). From the emission spectrum of these gases it has been found that there is an overlapping of the emissive bands of carbon dioxide and water vapor and therefore the total emission of a mixture of these gases cannot be the simple arithmetic sum of the separate emissions taken separately. There must exist a mutual absorption and emission in those parts of the spectrum that these gases mutually occupy. In the treatment that follows the total system pressure will be taken to be one atmosphere. For higher pressures the treatment given by Hottel (3) with appropriate correction factors for the increased pressures should be used. The work of Hottel and Egbert (5) gives an excellent critical comparison of data available on the subject of non-luminous radiation and also presents practical methods and graphs from which simplified calculation procedures may be devised. Since several summaries of this work (and also other fundamental information) are available in standard reference works (3, 4) only the necessary essentials will be given in this article.

Many workers in this field, notably Hottel, have found that for various practical shapes it is possible to treat these shapes as equivalent to a hemispherical volume of gas radiating to a spot at the center of the hemisphere and simultaneously this spot will radiate to the gas as a receiver. The radius of this equivalent hemisphere is called the mean beam length for radiation and has been found to be closely a function of the characteristic dimensions of the gas boundaries. Tabular values of this characteristic dimension are given in references (3) and (4) for many configurations that have been tediously evaluated by many investigators. Based upon the work of Port (6), it has been found that to a degree of accuracy that is generally satisfactory for most practical work, the mean beam length can be taken as being equal to 85% of the hydraulic radius of the gas mass and its boundaries. Figure 1 shows some typical tube banks in cross flow and based upon the typical dimensions shown in this figure. Figure 2 has been plotted giving the mean beam length as a function of these dimensions and the tube outside diameter. Actually these curves are correct for infinite tube banks as there is an error involved in a finite tube bank due to the bounding walls. In general this error is of a minor degree and does not introduce an appreciable error into the final results. However, any re-radiation from the bounding walls should be taken into account.

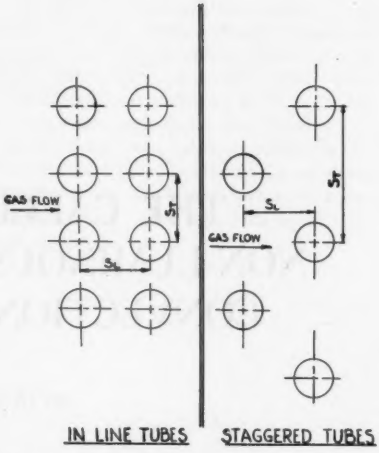


FIG. 1—Tube bank configurations.

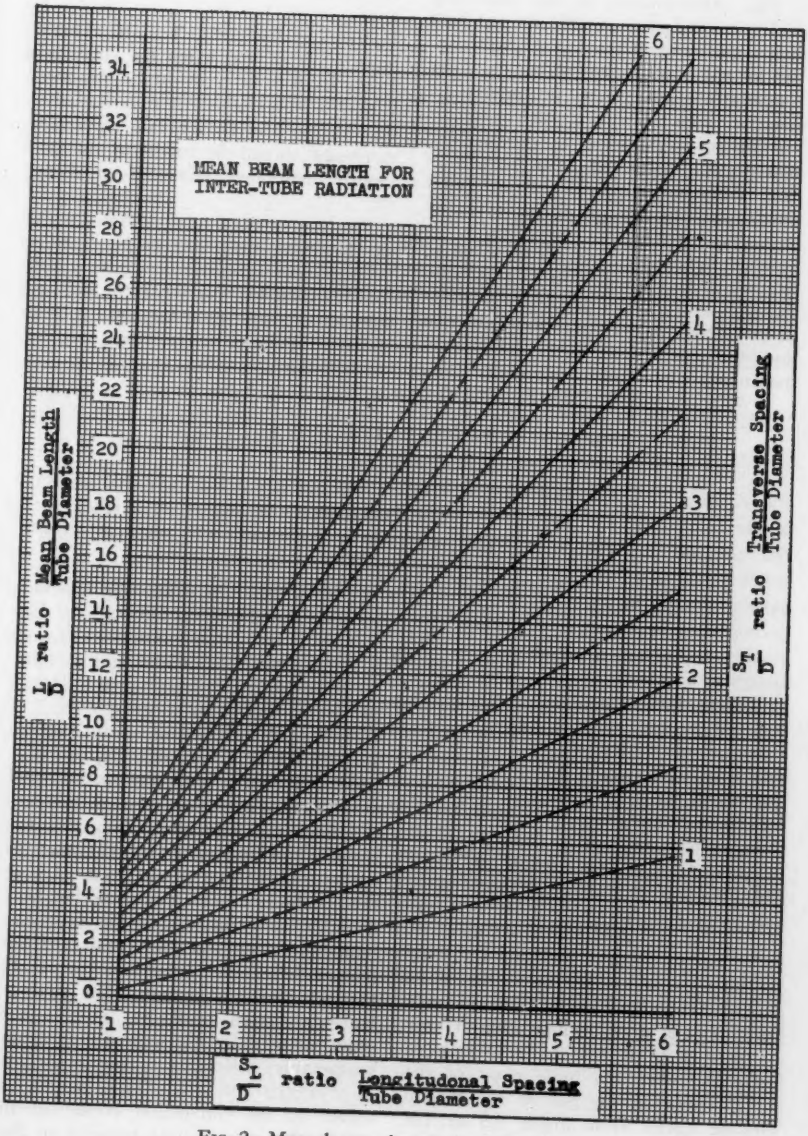


FIG. 2—Mean beam—length for cross flow.

The concentration of the radiating molecules and consequently the net heat flux depends upon the partial pressures of the radiating gases at a particular temperature and their intramolecular energy levels. Thus Hottel and his co-workers were able to express the emissivity of radiating gases as a function of the product of the mean beam length and the partial pressure of the radiating constituent. Dwyer (7) has presented convenient charts (from Hottel) which give the radiant heat transfer flux for both carbon dioxide and water vapor when each is present separately and the correction factor previously mentioned when both are present. The correction factor given by Dwyer is approximate but has been shown by Hottel and Egbert to lead to a maximum error of 4% when the correction factor itself is in error 50%. For those very few cases where it may be necessary to use a more accurate correction, reference should be made to the previously mentioned summaries of Hottel.

For the case of tube sections where the gas completely surrounds the tubes no angle correction is necessary. Thus for this case we may write the net heat transfer per unit area by non-luminous radiation (due to water vapor and carbon dioxide) as follows:

$$\frac{Q}{A} = e_g \left[(q_c + q_w) T_G - (q_c + q_w) T_s \right] \frac{100\text{-}K}{100} \qquad (1)$$

Based upon a typical fuel oil (1) the writer has plotted in Figure 3 the partial pressure of carbon dioxide and water vapor as a function of the percent carbon dioxide in the gas. The percent carbon dioxide is on a "dry basis" as would be obtained from an Orsat analysis. The mole ratio of water vapor to carbon dioxide in this gas from this fuel oil is very nearly equal to 0.7. Figure 3 was computed from perfect gas relations (2) which hold to a high degree of accuracy due to the high superheat of the gas components. From these curves and for various assumed products of mean beam length and partial pressure at various temperatures, calculations were made for the net heat absorption per unit area based upon an e_g of unity. Figure 4 shows the final working curve arrived at as described above. While this curve is based on a fuel oil of a given composition it may be used with a reasonable degree of accuracy when the mole ratio of the water vapor in the gas to the carbon dioxide varies from about 0.5 to 1.0. Also for the case of combustion gases in convection banks e_g may be taken effectively as unity. Of course the necessary correction for any other value is very easily made as can be seen from Equation (1).

In most cases the equipment in which the heat transfer is taking place is such that there may be a continuous change in temperature of both the gas and the surfaces from inlet to outlet. Hottel (4) states that to an adequate degree of accuracy an arithmetic mean surface temperature may be used. He also suggests that a mean gas temperature equal to the sum of the mean surface temperature plus the logarithmic mean of the temperature difference of the gas to surface at entrance and exit. Using these definitions one reads the net heat transfer from Figure 4 at the mean gas temperature and at the mean surface temperature. The difference represents the net heat interchange. The equivalent convection coefficient is this net value divided by the logarithmic mean temperature difference of gas to surface at entrance and exit. This should be added to the convection coefficient to obtain the correct heat transfer in the convection sections.

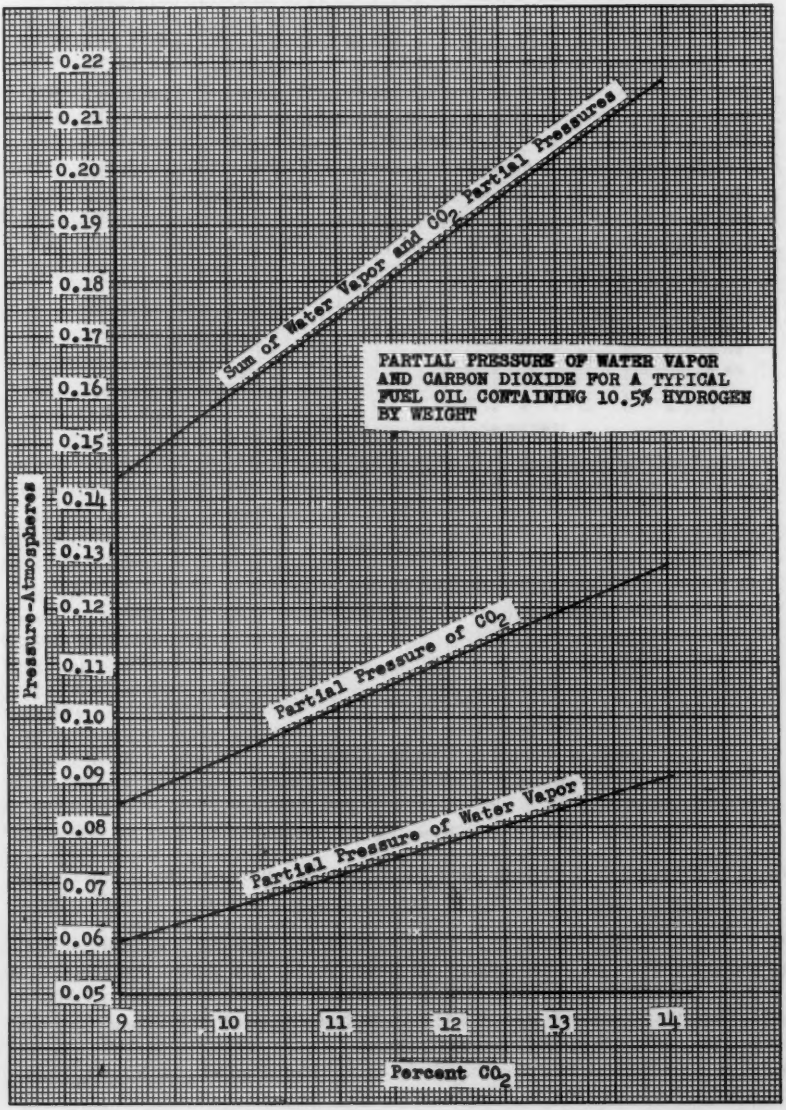
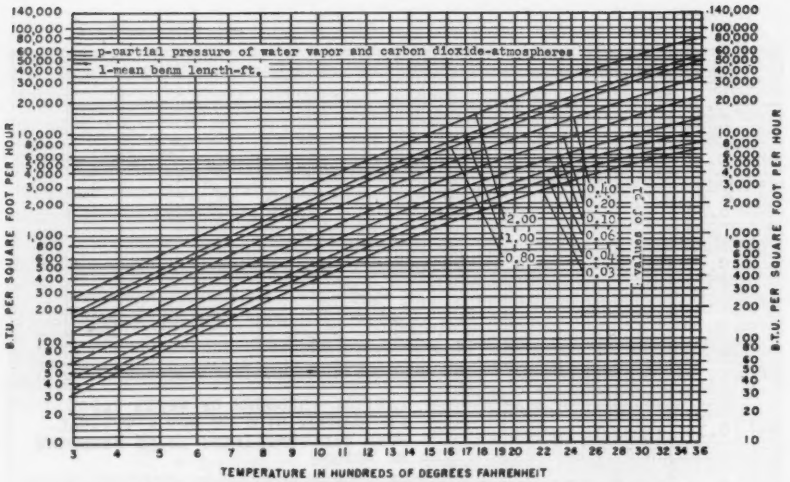


Fig. 3—Partial pressure of water vapor and CO_2 in a flue gas.



TOTAL RADIATION DUE TO WATER VAPOR AND CARBON DIOXIDE, FOR A FLUE GAS CONTAINING 0.7 MOL OF H_2O PER MOL OF CO_2.

FIG. 4.

NOMENCLATURE

Q = net heat transfer—BTU/hr.
A = area receiving radiation—sq. ft.
e_s = cold surface emissivity.
q_c = net heat transfer per unit area due to CO_2.
q_w = net heat transfer per unit area due to water vapor.
T_g = gas temperature—°R.
T_s = cold surface temperature—°R.
K = correction factor for interference—%.

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BOILER-WATER TREATMENT TO PREVENT CORROSION

ACKNOWLEDGMENT

This article is based on a paper presented at the "Journées internationales d'Etudes des Eaux de Chandiéres", at Liege on 4-6 May, 1953. Its author was V. R. EVANS. The abridged version was published in the 8 May, 1953, edition of "Engineering".

The author of this paper is not a specialist on boiler problems; nevertheless, it is possible that there may be some slight value in a paper which surveys them from the standpoint of fundamental corrosion science—at least, if it is read with papers by other authors, who approach the subject from different angles.

In the present paper, it has been necessary to rely too much on experimental data obtained at 100 deg. C. or lower, in discussing what is likely to happen at boiler temperatures; this necessity is regretted and any uncertainties thus introduced should be borne in mind by the reader. It is hoped that laboratory experiments, rather similar to those of Thiel and Luckmann, and of Gould, but carried out at higher temperatures, may become available in the future.

Boiler water receives treatment in order to prevent the formation of heat-obstructive scale, corrosion of the steel, and carry-over of matter by the steam. The avoidance of scale, if achieved, will itself do much to lessen chemical destruction, since oxidation on the fire side and, to a less extent, wet corrosion on the water side, becomes accelerated when there is overheating. Nevertheless, the problem of scale formation, as such, will not receive treatment in the present paper, which will be concerned only with the question: can we, by treating the water, prevent chemical destruction of the steel under conditions of normal thermal operation?

FUNDAMENTAL PRINCIPLES

T. V. Arden (1) has found that the solubility product of ferrous hydroxide is 2.4×10^{-14}, which is much higher than the figures obtained by some earlier workers who failed to remove traces of oxygen; thus the activity of Fe^{++} in neutral water ($pH = 7$) is $\frac{2.4 \times 10^{-14}}{10^{-14}}$, or 2.4, which is $10^{0.38}$. The potential of the electrode $FE \mid Fe^{++}$ (normal activity) is -0.441 volt on the hydrogen scale, so that the E.M.F. of the cell hydrogen|neutral water saturated with $Fe(OH)_2|Fe$ exerts an E.M.F. equal to $-(7 \times 0.058) - (-0.441 + (0.38 \times 0.029))$ volt; this is 24 millivolts, acting in such a direction that iron tends to enter the liquid, displacing hydrogen. That small E.M.F., provided that there is no formation of complexes, is independent of pH value, as pointed out by J. C. Warner (2). If the liquid

is made alkaline, the potential $H_2|H^+$ is shifted by 58 millivolts per pH unit, at room temperature, but the reduced solubility of ferrous hydroxide will shift the potential $Fe|Fe^{--}$ by the same amount. Any action of alkali in preventing the evolution of hydrogen by the action of water on iron must be ascribed, not to a diminution of the driving force, but to the production of conditions more favorable to film formation.

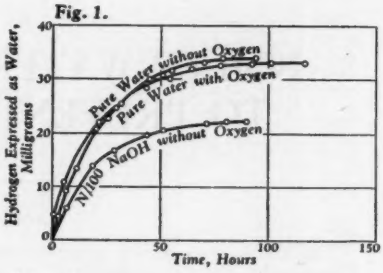
Such film formation, however, clearly occurs, even in neutral water. The curves obtained by A. Thiel and H. Luckmann (3) for the evolution of hydrogen by iron in water about 100 deg. C., shows that evolution is fast at first, but soon becomes slow (Fig. 1). A. J. Gould (4) studied the behavior of steel towards water in sealed tubes containing no oxygen. He found that, after 76 days at 100 deg. C., the destruction of metal (as measured by the loss of weight after removal of oxide) was only about 0.5 mg. on specimens measuring 7.5 × 10 cm.; before removal of oxide there was a gain in weight, suggesting a film of appreciable thickness. The film, after transfer to celluloid, was found to be magnetite; it is not inconceivable that it had been ferrous oxide on the metal and became oxidized during the transfer, but it seems more likely that it was already magnetite when adhering to the metal. Probably, the ferrous hydroxide formed by the action of boiling water on iron

$$Fe + 2H_2O = Fe(OH)_2 + H_2$$

is changed to magnetite by Schikorr's reaction (5)

$$3\ Fe(OH)_2 = Fe_3O_4 + 2H_2O + H_2.$$

Fig. 1.



J. N. Wanklyn (6) found that Schikorr's reaction does not occur readily in the absence of a catalyst, but that it takes place if metallic nickel, copper or platinum are present. Although the result was not verified on an iron surface, it seems likely that magnetite will slowly be deposited on steel from boiling water containing ferrous hydroxide; or that, if a film of solid ferrous oxide or ferrous hydroxide has been deposited on steel, it will sooner or later change to magnetite, with the evolution of hydrogen. Whatever the exact composition of the film, the cessation of hydrogen evolution is easily understood, provided that the film is continuous over the surface. Anything which favors the formation of closely spaced nuclei (whether of magnetite, ferrous hydroxide or ferrous oxide) on the surface will promote the formation of a continuous protective film, and, consequently, the cessation of attack. Conversely, anything which favors the precipitate of oxide or hydroxide at a distance from the metal will encourage the continuation of attack.

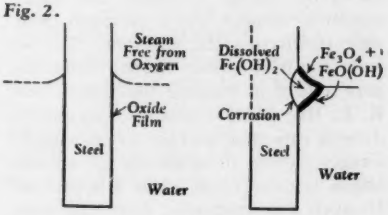
THE EFFECT OF OXYGEN

Although Thiel and Luckmann's curves (Fig. 1) show that the presence of oxygen does not increase the hydrogen evolution, it causes much corrosion of another type. Gould compared the behavior of iron standing partly immersed in boiling water with only oxygen-free steam above the liquid, and iron standing partly immersed in boiling water with access of air to the space

above the liquid. In absence of oxygen, attack soon became slow—doubtless through film-formation on the metallic surface, the weight loss being about 0.5 mg. after 76 days. When air had access, the weight loss was 365.2 mg. in the same period. Probably, part of the ferrous hydroxide formed near the waterline passed into solution, and, meeting dissolved oxygen, was transformed into magnetite (Fe_3O_4) or hydrated ferric oxide ($Fe_2O_3.H_2O$ or $FeO(OH)$) at a slight distance from the metal (see Fig. 2). Solid formed at a distance cannot prevent attack, and the destruction of dissolved ferrous hydroxide prevents the attainment of the high state of supersaturation with ferrous hydroxide which would be needed for the formation of a continuous film of ferrous hydroxide or ferrous oxide on the metal itself; when once it has started, any magnetite formed by Schikorr's reaction will probably be deposited on the existing magnetite at a distance from the site of attack in preference to the formation of fresh nuclei. This explains why Gould found that, when oxygen was present, the crust of magnetite formed near the waterline adhered to the metal only at a few points. The magnetite here was mixed with hydrated ferric oxide (rust); both compounds appeared to have been formed at the water-air interface, where oxygen is present, rather than the metal-water interface. When this semi adherent crust was removed, the iron was found to be deeply pitted and trenched.

In working boilers, the temperature will be higher, but probably the same principles apply; the supply of oxygen should be insufficient to form rust, but it may be sufficient to bring the place of formation of magnetite to a slight distance from the metal, which locally develops no protective film, so that pitting arises. Clearly, if the oxygen reaches certain areas of the boiler surface only, other parts being screened, conditions become particularly favorable for attack, which will be most intense when the screened area is small. G. P. Acock, T. Dennison, P. T. Gilbert and R. S. Thornhill (7) write that "Corrosion is sometimes found under scale or other deposits. . . . The reason is probably differential aeration, i.e., the shielded metal, receiving a poorer supply of oxygen than the areas surrounding it, becomes anodic and is attacked." They add that corrosion below deposits may also be due to the concentration of alkali and other salts; temperatures and concentration may locally be reached at which attack becomes rapid. M. Werner (8) also discusses corrosion below deposits in high-pressure boilers. A. A. Berk (9) assigns an important role to the ferrous iron introduced from the pre-boiler system in producing intensified attack at screened areas.

Fig. 2.



THE EFFECT OF ALKALI

By increasing the $(OH)^-$ activity, the solubility of all the oxides and hydroxides is reduced, and the degree of supersaturation set up in the liquid very close to the metal is raised. This will clearly favor the production of closely-spaced nuclei of one of the three compounds, and promote the formation of a protective film; thus alkali additions to boiler-water may overcome the bad effect of oxygen. Gould's laboratory measurements, in the presence of air,

record lower weight losses in N/100 sodium hydroxide than in pure water. In the absence of oxygen, his results permit of no definite conclusions regarding the effect of alkali, but Thiel and Luckmann's curves (Fig. 1) suggest that the oxide film becomes protective after a smaller evolution of hydrogen (i.e., after a smaller destruction of metal) in dilute alkali than in neutral water. These observations accord with practical experience; the subject has received convenient treatment by I. G. Slater and N. L. Parr (10).

THE EFFECT OF METALLIC COPPER

Boiler water often contains copper, derived from condenser tubes or other parts outside the boiler proper which consist of copper or copper alloy. This will not necessarily be harmful. Sometimes the copper is precipitated as oxide, basic carbonate or phosphate, and passes out with the sludge. In other cases, the water contains dissolved copper salts without metallic copper being thrown down on the steel. In an acid solution of a copper salt, which should not exist in a boiler, iron would pass into solution, precipitating metallic copper. In an alkaline solution, copper ions can normally exist only at very low concentrations, and, in any case, the iron (becoming passive, owing to film formation, as already explained) is unlikely to precipitate metallic copper. It seems, however, that certain waters, containing ammonia or ammonia derivatives introduced by sewage pollution, can attack copper or copper alloys (oxygen probably facilitating the reaction) and yet leave the iron active. Perhaps chlorides play a part in keeping the iron active. R. L. Rees (11) considers that carbon dioxide can attack copper in presence of oxygen, even if ammonia is absent; attack is more rapid when it is present. In such circumstances, iron can enter the liquid, precipitating copper in a metallic form, sufficiently clean to act as a catalyst for Schikorr's reaction; Wanklyn found that metallic copper catalyzed that reaction efficiently, even at room temperature. If this occurs in a boiler, then ferrous hydroxide, produced by the reaction of water on iron at breaks in the magnetite scale, will deposit fresh magnetite, not on the steel exposed at the break (which, in that case, would be repaired) but on an adjacent speck of metallic copper. Thus the magnetite round the copper will thicken, but, when the original copper has been buried, more may be deposited, and thus the process goes on, producing a pit surrounded by very thick magnetite scale with embedded specks or microscopic flakes of metallic copper.

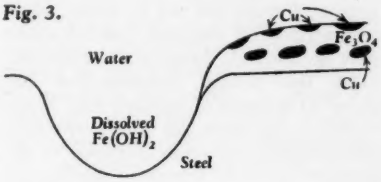
Pitting associated with thick magnetite scale containing metallic copper has been observed at power stations (12). The features of this type of corrosion are: (1) the copper is often deposited upon the magnetite and also on bare steel at places where the steel is uncorroded; (2) specks of copper are included in the magnetite and, indeed, there may be layers of metallic copper laminated in between layers of magnetite; (3) at places where there is corrosion, the magnetite, although clinging to the steel at a few points, is not always in continuous contact with the steel—a cavity often exists between the two, although sometimes pits are found which appear to be tightly plugged to the bottom; and (4) the magnetite is laminated and can grow to considerable thicknesses near the points of attack.

These facts suggest that iron is passing into solution at certain points, giving a solution of ferrous hydroxide, which becomes converted to magnetite by the Schikorr reaction—not, for the most part, at the point of formation (where it would produce a protective film) but preferentially on the copper

specks; when these become embedded in the freshly deposited magnetite, fresh copper is deposited upon the magnetite as cathode, steel exposed at the point of corrosion providing the anode. The scheme is suggested in Fig. 3 which is purely diagrammatic and may not represent the true geometry of the system.

The interpretation sketched above is put forward tentatively, but does serve to explain the facts known to the author without *ad hoc* assumptions. Other explanations (13) are possible. Berk, for instance, considers that the hydrogen produced by the Schikorr reaction during the partial oxidation of ferrous iron introduced with the feed-water can and does precipitate metallic copper, which, in certain cases, may promote carbuncle pitting.

Fig. 3.



MAIN REQUIREMENTS FOR BOILER WATER

If we leave aside the dangers involved in the presence of copper, the two main requirements for avoiding corrosion are the absence of oxygen and an adequate reservoir of $(OH)^-$. Today, the bulk of the oxygen is commonly removed by thermal methods, which also take out the nitrogen, but it is generally believed that chemical methods are needed to eliminate the last traces. If this is true, it would seem desirable to improve the thermal methods, so that they can remove the whole of the dissolved gases. Chemical methods, whether based on sulphite or hydrazine, do not remove the nitrogen; the hydrazine method may even increase it. Nitrogen pockets are often assumed to be harmless, although there seems to be no proof of this. The use of sulphite increases the dissolved solids, may produce sulphur dioxide if the water should become temporarily or locally acid, and may give rise to hydrogen sulphide, in certain circumstances not clearly defined; both of these compounds can be dangerous.

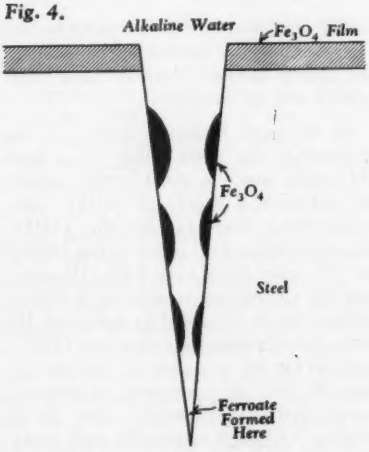
An adequate hydroxyl reserve is not necessarily the same thing as a high *p*H value, since a good buffer system can maintain a supply of $(OH)^-$ ions, replenishing very rapidly the $(OH)^-$ ions used up in film repair, even though the *p*H value is not very high. Provided that the replenishment rate by a buffer-system can be regarded as sufficient, the plan of maintaining the required $(OH)^-$ content by the presence of sodium hydroxide (or of carbonate, which becomes hydroxide) would seem to be illogical, although commonly used today. However, the main objections to reliance on sodium hydroxide as the source of OH^- are the dangers of carry-over and of cracking.

THE ACTION OF CONCENTRATED ALKALI ON METAL

Most metals are dissolved by acids forming soluble salts; in liquids of *p*H value somewhat above 7, where the corrosion-product would be a sparingly soluble oxide or hydroxide, there is little attack, but in definitely alkaline solutions attack is again met with in many cases; thus zinc dissolves to form a zincate, aluminium as an aluminate, tin as a stannite and lead as a plumbite. Iron differs from the four metals just mentioned in that a really high concentration of alkali and a slightly elevated temperature is needed for the for-

mation of sodium ferroate (Na_2FeO_2) —which corresponds to sodium zincate (Na_2ZnO_2). The alkali concentrations needed will not normally occur in the body of the water in a boiler, but if there is a leakage path, as may exist at imperfect riveted joints or imperfect flanged couplings, which allows the escape of steam but not of water, alkali may accumulate and high concentrations may be reached. Some authorities consider that similar concentration can occur in absence of leakage, e.g., below deposits, or even on clean surfaces, when bubble formation is rapid, in the crevices formed between bubble and metal.

Fig. 4.



The reaction of iron with hot concentrated sodium-hydroxide solution would excite less alarm if it were well spread out. Unfortunately, with steel under tensional stress, there is frequently a preferential attack along the grain boundaries, and cracking occurs. The metal is apparently attacked at the tip of a crack as it advances into the metal, forming a solution of sodium ferroate; at a short distance from the place of formation, the ferroate decomposes, throwing down magnetite, either with evolution of hydrogen, by a reaction of the Schikorr type, or through the action of oxygen or an oxidizing agent,

$$3Na_2FeO_2 + 4H_2O = 6NaOH + Fe_3O_4 + 2H$$

$$3Na_2FeO_2 + 3H_2O + O = 6NaOH + FE_3O_4.$$

Thus magnetite appears in the cracks, although at an appreciable distance from the point of formation of the ferroate, as suggested diagrammatically in Fig. 4.

The sodium ferroate may decompose at a distance from its point of formation either because it becomes diluted (the ferroate is only stable in presence of excess of alkali) or because it meets with oxygen. C. D. Weir (14) observes that the large fissures are filled with ferroso-ferric oxide, with smaller amounts of ferrous oxide, but that associated with each large fissure is a network of very fine subsidiary intergranular cracks, many of which appear to be free from corrosion products. E. W. Colbeck, S. H. Smith and L. Powell (15) state that there are only slight signs of thin oxide inside the fine intergranular cracks, although there is a crystalline deposit of black magnetic oxide outside the crack; they describe, however, a second type of straight, blunt-ended transgranular cracks which are filled with corrosion products. Berk states that many cracks which appear to be free from magnetite are found to contain it when examined at higher magnification. He thinks that magnetite is formed at the tips of the cracks, and that the attack continues only because magnetite is brittle.

To the author, it seems more likely that magnetite is a secondary product, deposited from solution at a distance from the point of attack—the tip of the advancing crack. Because of the point of formation, the magnetite cannot stop the attack. If, however, an oxidizing agent more soluble than oxygen were supplied in sufficient quantity to con-

vert ferroate into magnetite at the point where the ferroate is formed, the attack might cease. This may be the cause of the prevention of caustic cracking brought about by the presence of nitrate, which furnishes oxidizing anions capable of moving rapidly towards the anodic region (the tip of the advancing crack) under the electric potential gradient, whereas the uncharged oxygen molecules can only move slowly by diffusion under a very low concentration-gradient; but the explanation is put forward tentatively.

Whether ferroate is changed to magnetite by the adsorption of oxygen or the evolution of hydrogen, the sodium hydroxide is regenerated in full; but, in the Schikorr type of reaction, atomic hydrogen may enter the metal, increasing the inter-crystalline fragility. There is no definite proof that this occurs, but the idea of local embrittlement caused by hydrogen-formation at the crack-tips causing local embrittlement would agree with views now developing for other cases of stress-corrosion cracking; it should be noted that the steel between the cracks is not brittle. It seems unlikely that hydrogen produces cracking by converting carbon to a hydrocarbon gas—as seems to be claimed by C. A. Zappfe (16).

NITRATE CRACKING AND CAUSTIC CRACKING

Surprise is sometimes expressed at the fact that nitrates, which tend to prevent cracking in highly alkaline liquid, can cause cracking under slightly acid conditions; steel stressed in a hot concentrated solution of the nitrate of a weak base (which solution will react slightly acid) suffers intergranular cracking, leading rapidly to fracture. However, analogous cases could be cited: small amounts of chromates prevent corrosion in neutral or weakly alkaline liquids, but accelerate corrosion by dilute sulphuric acid; indeed, most oxidizing agents are cathodic stimulators and anodic inhibitors, and the alleged paradox has no reality.

The relation between nitrate-cracking and caustic-cracking deserves study. Steel in a boiling ammonium-nitrate solution becomes covered with a layer of magnetite, which would be protective if it were continuous, but usually it becomes broken in places, and the steel there exposed suffers intense attack; the combination of large cathode (the scale) and small anode (the steel exposed) favors intensity, for well-known electrochemical reasons. If the steel is one in which the intergranular layers are more susceptible than the grains themselves, and if it is kept under tensile stress, the attack will constitute cracking.

The fact that a nitrate solution which produces a protective magnetite coat over the outer face of the metal, fails to produce protection at the tip of the advancing crack may be due to a lower concentration (due to a lower rate of replenishment) within the crack; perhaps also, the stress keeps breaking any obstructive oxide formed at the tip of the crack. However, not all steels possess the intergranular paths of susceptible matter needed for nitrate cracking. R. N. Parkins (17) finds that steels containing carbide particles along the grain-boundaries are susceptible to nitrate-cracking; by applying a heat-treatment which produces such a structure, he has converted a resistant steel into a susceptible one. The attack does not fall upon the carbide particles, but upon the ferrite along the grain boundaries, which is considered to be kept in stress owing to the difference between the coefficients of thermal expansion of carbide and ferrite respectively. This highly stressed ferrite at the grain boundary will suffer anodic attack in preference to the less stressed grain

interiors (18) and the crack will advance mainly along intergranular paths running roughly at right angles to the direction of the applied stress—explaining the facts observed.

Caustic cracking has some points in common with nitrate cracking, but some important differences. The magnetite layer covering the face of the steel probably acts as the big cathode at the outset, with the tips of the incipient cracks as the small anodes. However, the deposition of magnetite in the cracks as they advance may serve to provide new cathodes relatively close to the anodes, so that the resistance of the corrosion cells is kept low—an occurrence favorable to the advance of the cracks. Moreover, the attack appears to fall not on the ferrite, but on the carbide—particularly in the pearlite regions—an important fact observed independently by C. D. Weir (19) and by G. A. Cottell (20). An explanation can be suggested. The dioxide of carbon has pronounced acidic properties, while the oxides of iron have only feeble acidic properties; thus attack by alkali on a phase which can furnish sodium carbonate as well as ferroate may be expected to proceed more readily than one which would furnish ferroate alone.

For this reason, the steels which are most resistant to nitrate-cracking will not necessarily resist caustic-cracking; indeed, although steels differ among themselves in liability to cracking in caustic, none are immune from the trouble. On the other hand, caustic cracking seems to occur more easily when there is a rather complicated non-uniform stress condition—as brought out by Colbeck, Smith and Powell, *loc. cit.* Badly aligned rivets produce conditions favorable to caustic cracking, perhaps because they favor leakage and hence concentration of sodium hydroxide. The packing pieces of double butt-strap seams sometimes crack to a surprising extent, and unwise caulking can produce a non-uniform stress very conductive to caustic cracking—points emphasized by Cottell.

The Schroeder-Berk embrittlement detector (21), a device which can be fitted to a working boiler and sets up cracking conditions by concentrating the water through evaporative leakage in contact with a stressed-steel specimen, has practical value for distinguishing a water capable of producing cracking from one which is not immediately dangerous.

AVOIDANCE OF CAUSTIC CRACKING

If boiler water is given its necessary alkalinity by the presence of sodium hydroxide, it may be only a matter of time before leakage locally raises the concentration of caustic to a dangerous level. In practice, it is found that caustic cracking often does take a long period to develop; if there is no leak, it may never develop at all. It is impossible to state a critical alkali concentration below which a boiler water can be regarded as "safe"; however low the concentration may be in the body of the water, the risk remains that a dangerous level may ultimately be reached in the seams.

If, however, the water contains sodium phosphate with a ratio of Na_2O/P_2O_5 slightly lower than that corresponding to a solution of pure Na_3PO_4, then a concentration of $(OH)^-$ can be maintained by hydrolysis in the body of the water, apparently sufficient to prevent ordinary corrosion, but without risk of excessive $(OH)^-$ concentration in seams or recesses; for, when once concentration has reached the level at which solid Na_3PO_4 is thrown out, the concentration of $(OH)^-$ cannot rise further. Practical experience has shown that the maximum $(OH)^-$ concentration thus reached is below the

dangerous limit. In general, it is not necessary to add trisodium phosphate. If the water is already alkaline, common sodium phosphate ($Na_2HPO_4 . 12H_2O$) or Calgon $(NaPO_3)_n$, which changes to NaH_2PO_4 under boiler conditions, may be added in appropriate amount. Berk (22) gives favorable accounts of the employment of this method in the United States of America—where it was worked out; P. Hamer and C. D. Weir (23) discuss its application in Great Britain.

Other methods for preventing caustic cracking include nitrate treatment, which appears to have met with considerable success on American railways; a tentative explanation has been offered above: Weir and Hamer, basing their recommendation on American experience, suggest that the ratio of $NaNO_3$ to total alkalinity, expressed as NaOH, should be 0.4. Treatment with quebracho or other tannin has also been helpful, the ratio being again 0.4.

THE SULPHATE-RATIO CONTROVERSY

The belief that caustic cracking can be controlled by maintaining the ratio of Na_2SO_4 to alkalinity above a certain value was put forward in the United States many years ago, on evidence which today appears somewhat unconvincing. Lately, the method has been widely advocated in Great Britain, though simultaneously faith in its efficacy has faded in its country of origin—particularly in railway circles, where some sharp criticism has been expressed. Thus a report issued by the American Railway Engineers' Association (24) states: "On the railroads it was found that embrittlement was occurring in boilers where high sulphate-hydroxide ratios were maintained and no embrittlement was being experienced with feed water containing no sulphate and a very high sodium carbonate content. The sodium carbonate hydrolyzed into sodium hydroxide in excessive amounts at boiler temperature . . . Due to the fact that the sulphate-hydroxide ratio maintained in steam boilers was found worthless as an inhibitor in railroad service, . . . it is the opinion of your Committee that the railroads should disregard the sodium-sulphate/hydroxide ratio recommendations, as outlined in the American Society of Mechanical Engineers Boiler Code of 1940. . . . "

They recommend the properly supervised and controlled use of sodium nitrate or lignin in water known to have embrittling tendencies; proper workmanship, resulting in tight boiler seams; and the installation of embrittlement detectors on boilers operating in suspected-water districts. The effectiveness of nitrate (and, to a less extent, quebracho) in locomotive and stationary boilers is shown by recent figures supplied by Berk.

The sulphate-ratio method is supposed to work (to quote Weir and Hamer) "either by the deposition of solid sodium sulphate on the highly stressed parts of the boiler-plate or by plugging a seam"; the same authorities suggest that it may sometimes be calcium sulphate which forms the protective layer. Statistical analysis of the results obtained with the sulphate-ratio method by Weir (25) appears to indicate that it is without value. Weir's analysis, however, has been criticized on the grounds that the classification of waters as cracking and non-cracking was made by means of the Schroeder-Berk detector—not by direct observation on working boilers; it has been argued that, however valuable the detector may be for appraising the essential cracking

powers of a water, it is less suitable for estimating the plugging properties.

A high-sulphate ratio may be obtained by keeping the $(OH)^-$ low as well as by keeping the $(SO_4)^{--}$ high. It is generally agreed that high $(OH)^-$ is dangerous, although opinion varies upon the question as to whether $(SO_4)^{--}$ is beneficial. In early days, it was not unusual to treat a dangerous water, rich in OH^-, with sulphuric acid or magnesium sulphate; apparently with some success, provided that the additions were made with restraint, since some OH^- is needed to prevent other types of attack. Here any beneficial effects could be attributed to the lowering of the $(OH)^-$ rather than the increase of the SO_4^{--} concentration (*26*). For some reason, however, it came to be believed that a high $\frac{(SO_4)^{--}}{OH^-}$ ratio (rather than a low value for the absolute OH^- concentration) was the essential criterion for safety; and boiler owners today are being recommended to add sodium sulphate, which increases the $(SO_4)^{--}$ concentration without greatly affecting the $(OH)^-$ concentration. It is confidently asserted in this country that such a treatment usually prevents cracking where otherwise it would occur, although it is now admitted that the method sometimes fails. In a plant where careful and continuous observations show that, in point of fact, water thus treated is not producing cracking, it would be rash to suggest a change in procedure; but it would be impossible to feel confident that the same treatment applied in a new plant would also prevent cracking.

The British Electricity Authority are proposing to use, at some power stations, the sulphate-ratio method along with the nitrate method, thus establishing two lines of defense. In the present state of knowledge, this seems a prudent course. If the chance of cracking in the doubly-protected boiler is the product of the chances in two boilers singly protected by each of the methods, it is the product of two small quantities and therefore negligible. However, this argument is only valid if the protective mechanisms are so dissimilar that there is no correlation between the incidence of breakdowns under the two processes; the doubts which arise in deciding the question of possible correlation underline the practical importance of greater understanding of the manner in which these protective processes operate.

COMMON FEATURES OF ALL TYPES OF CORROSION

Each kind of trouble discussed above can be related to a single cause. An oxide (usually magnetite) which, under normal working, would be produced as a continuous adherent protective skin, capable of hindering further attack, is, under exceptional conditions, thrown down at certain points at an appreciable distance from the surface, where it cannot protect the steel. Various unfavorable factors may produce this undesired result. The iron may pass into solution as ferrous hydroxide and be transformed to magnetite a short distance away, at a point to which oxygen has access; or it may pass into solution as ferrous hydroxide and be transformed to magnetite (with hydrogen evolution) at a short distance, where metallic copper—a catalyst for the Schikorr reaction—has been deposited; or it may pass into solution in strongly alkaline crevices as sodium ferroates, which may be transformed to magnetite at a short distance, where the liquid becomes diluted or where oxygen is available.

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26. Although theoretically a very low initial $(OH)^-$ concentration in a seam might in time reach a dangerous level by evaporative leakage, this postulates that geometrical conditions under which there is no exchange of liquid between the seam and the body of the boiler water other than the entry into the seam of sufficient liquid to compensate for loss by leakage. If free mixing takes place between the water in the seam and that in the body of the boiler, the concentration process must start afresh. During the long period needed to reach the dangerous level when the initial concentration is low, this free mixing is likely to occur from time to time. Thus if the $(OH)^-$ concentration in the body of the boiler water is kept low, the danger of cracking is small—even though the chance of other types of corrosion becomes enhanced.

HOW TO CONTROL MARINE CORROSION WITH GALVANIC ANODES

ACKNOWLEDGMENT

This article discusses the use of magnesium anodes to control hull corrosion. It was written by MR. R. D. TAYLOR, and was published in the June 1953 issue of "Marine Engineering."

The financial cost of corrosion to the marine industry runs into billions, not just millions, of dollars annually. The corrosion of steel submerged in sea water or buried in the ground is an electrochemical phenomenon. As buried or submerged steel rusts or corrodes, minute electric currents are flowing from various areas on the surface of the metal into the sea water or earth and back to the source through some metallic path. In this process the iron is actually destroyed, leaving a completely useless residue we know as rust. This corrosive action can and is being effectively controlled through the use of magnesium anodes. When electrically connected to a steel structure in the presence of sea water or moist earth magnesium anodes will generate an electrical current of sufficient magnitude to offset the weaker current produced by the local corrosion cell action of unprotected steel. Thus corrosion is prevented by sacrificing an expendable magnesium anode. It also can be accomplished effectively in some cases with zinc anodes or with non-expendable anodes coupled to an external source of direct current.

Magnesium galvanic anodes are today being used for the protection of water, oil and gas pipe lines, storage tanks, ballast compartments in tankers, tank barges and cargo ships, steel piers and piling, off-shore drilling platforms, and the underwater hull surfaces of active and laid-up vessels. Cathodic protection with magnesium galvanic anodes is a standard requirement following well-established procedures in the Canadian Navy and it also is under active test by our own Navy on both active and dormant vessels. The U. S. Maritime Administration has installed a full-scale cathodic protection program using magnesium anodes on a reserve fleet of approximately four hundred ships. Thus, cathodic protection is not just an idle theory but a working method of controlling sea water and underground corrosion.

Lest one get the impression that the principles discussed here are entirely new and novel, it is well to point out that Sir Humphrey Davy in 1824, defined and applied the identical principles by using pieces of iron as anodes to protect the copper sheathing of wooden vessels in the British Navy.

In those days magnesium was virtually unknown. Today, it is a common metal used for all manner of structural purposes in addition to its use as a galvanic anode. In passing, it is perhaps of interest to point out that magnesium, aside from its virtues of light weight, easy machinability, rigidity, good damping and deep drawing characteristics, is in virtually inexhaustible supply. The bulk of our magnesium today is obtained from sea water, one cubic mile of which contains 6,000,000 tons of recoverable magnesium. A recent article in *Life* magazine reports that there are 300,000,000 cubic miles of sea water on this earth of ours. This represents a lot of magnesium any way you look at it. Some one has estimated that if we were to take 100,000,000 tons of magnesium from the sea for 100,000,000 years, the magnesium content of the water would be reduced from 0.013 to 0.012 percent—that is, if no additional metal was washed into the sea in the meantime.

PRINCIPLES OF GALVANIC ACTION

To return to the principles of galvanic action, let us examine some of the reasons for metals behaving as they do. All metals exhibit a tendency to revert to their original state of ores or compounds as found in nature. Every metal is either anodic or cathodic with respect to other metals. When two dissimilar metals are coupled together in the presence of an electrolyte such as sea water or moist soil, a galvanic cell is formed and the more anodic metal will corrode while the other will be protected.

The various metals and alloys thus all possess a definite electrical potential in respect to a particular environment. As a result they can be arranged according to what is known as the galvanic series given in Table I.

Table I

THE GALVANIC SERIES

Corroded end (anodic or least noble)
- Magnesium
- Aluminum
- Zinc
- Cadmium
- Iron or steel
- Stainless steels (active)
- Soft solders
- Tin
- Lead
- Nickel
- Brasses
- Bronzes
- Nickel-copper alloys
- Copper
- Stainless steels (passive)
- Silver
- Graphite
- Gold
- Platinum

Protected end (cathodic or most noble)

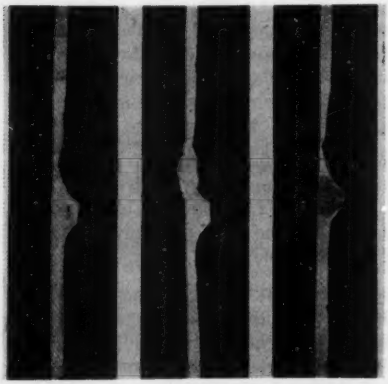
Magnesium stands at the top of the list as the most anodic of our common metals. Magnesium has a potential of −1.5 v to a copper/copper sulphate reference electrode. Bare steel has a similar potential of about −0.4 v. Thus, when magnesium and bare steel are connected electrically in the presence of an electrolyte, such as sea water, the driving potential of magnesium, the anode in the circuit, will be approximately 1.1 v. In this "battery" the amount of current flow will be determined by the resistance in the circuit. This in turn is composed of the resistivity of the sea water or soil as the electrolyte, the resistance to the electrolyte of the structure being protected and the resistance of the connection between the anode and the structure. Experience has shown that if the potential of the base steel can be shifted to −0.85 v, corrosion of the steel can be stopped. This result can be demonstrated readily by placing a piece of bare steel connected to a small piece of magnesium in a glass of ordinary tap

Fig. 1 After side of T-3 tanker transverse bulkhead showing localized thinning at horizontal web stiffener

water. No corrosion will result. A similar piece of bare steel without the magnesium placed in another glass of water will begin to corrode within a matter of hours.

The corrosion of steel in sea water, as we normally see it, represents countless tiny batteries in the form of galvanic cells. These cells are the result of a dissimilarity of some sort—either between two different metals or different areas of the same metal. The most common example perhaps is that of the bronze propeller on a steel vessel. Others include dissimilar metals in condensers, heat exchangers, valves, piping, and similar apparatus. Ordinary steel plate may have areas of different potential due to mill scale, rust or weld effects, Figs. 1-2. Joining of new plates to old ones also may result in anodic and cathodic areas. The natural weathering of steel plates in shipyards helps to eliminate one source of trouble by loosening the mill scale. In some alloys, the very components of the alloy may be responsible for tiny galvanic cells with resulting corrosion. This is most pronounced in alloys where one or more of the ingredients are present in amounts in excess of their solid solubility in the parent metal.

Corrosion difficulties also can result from electrolysis caused by stray currents. Improperly grounded welding generators used on ships may be a cause of this type of corrosive attack.



(a) *(b)* *(c)*

Fig. 2 Sections showing localized thinning of bulkhead plates

(a—Section of plate shown in Fig. 1; thinning at horizontal web stiffener. *b*—Another T-3 transverse bulkhead specimen, showing weld metal used in attempt to control localized thinning of web stiffener. *c*—Section, taken 4 in. from that in *b;* evidentiy localized thinning occurred after that in *b* had been built up with weld metal. This shows futility of method of trying to correct problem.)

SURFACE PROTECTION

The time-honored method for combating corrosion is, of course, through the use of paint or other methods of surface protection. The method is still sound and economical but paint alone can never do the whole job. Paints have been improved steadily over the years along with methods of preparing the surface and applying the paint. However, one simple fact must be acknowledged and that is that a paint job is no better than the surface preparation, the quality of the paint and the care with which it is applied. With the human element involved there is no such thing as a perfect paint job. Hand or machine chipping, wire brushing and even sand or grit blasting are anything but foolproof. There has yet to be developed a paint which is completely impervious to moisture or which can be applied with freedom from holidays or imperfections. There has been virtually no success in painting the interior surfaces of ballast compartments in tankers, both because of the action between most paints and the cargo and because of the practical impossibility of cleaning the tanks and applying the paint properly. The outside surfaces of a hull are, of course, more readily accessible for cleaning and painting. The problem comes in protecting the surface where the paint film becomes damaged for one reason or another.

PROTECTIVE ACTION OF CATHODES

This is where cathodic protection steps into the act. A properly designed cathodic protection system will provide current to offset corrosion on such bare surfaces where it is needed, when it is needed, and in the amount needed without the necessity for manual attention or mechanical apparatus of any sort.

The effectiveness of such a system can be determined readily by visual inspection and can be confirmed by electrical measurement. The first result is a descaling of the bare steel being protected. It begins immediately and continues until virtually all scale has been loosened. For example, in a six-year-old T-2 tanker, a total of 138 tons of scale, the equivalent of 97 tons of steel, were removed during the first year from the three sets of tanks put under protection. No new scale is being formed. The second result is the laying down of a white or tan colored calcareous deposit when protection is being afforded. This is first noted in areas adjacent to the anodes but spreads out as these local areas become polarized and require less current.

The same effects can be noted on the exterior underwater hull surfaces. Scale is either removed or loosened so that it comes off readily when preparing for the next paint job. Calcareous deposits will be found on bare steel areas though to a lesser degree than on interior surfaces owing to the abrading effect of the ship's movement in the water. Test patches prepared on hulls with paint in poor condition have been found to be clean and bright after removal of marine growth, in dry dockings at intervals of 6 months and 1 year. Thus, when the cost of docking a vessel and applying a multi-coat paint system can run to as much as $20,000 it makes sense also to supply cathodic protection for those areas where the paint may not hold, may be lacking entirely as at chock block marks, or where the paint system may become damaged. If this is not done, severe corrosive attack is likely to be concentrated in these areas, thus accelerating troubles which the paint was supposed to prevent.

In a fashion, this situation illustrates a violation of one of the fundamental

principles of corrosion control; i.e. that the anode area should be kept large in relation to the cathode area in order to avoid concentrated corrosive attack. Thus, when a paint system is applied to a steel hull, various anodic and cathodic areas are given a protective coating but also the total anodic area represented by the bare spots on the hull is drastically reduced in relation to a known cathodic area represented by the bronze propeller. This gives rise to the familiar condition of concentrated attack found at bare spots particularly in the stern-frame area. It is not difficult to understand this rate of attack for 1 amp. of current flowing from bare steel for one year will remove 20 lb. of steel as rust.

A comparable situation is found in the pipe-line industry where lines are often coated at considerable expense with an elaborate system of cleaning and applying enamels, asphalts, and fibered wrappings. Before placing the pipe in the ground, the coating is checked for breaks or holidays with electrical instruments. Subsequent breaks which inevitably occur in the coating, resulting from the backfilling operation, are located electrically and the pipe is uncovered for coating repairs. An undetected break in the coating can cause a rapid failure of the pipe in spite of the expensive precautions taken in applying the coating. The paint system on a vessel hull on the other hand is not subjected to this careful checking and when damaged in service cannot be repaired until the next docking. Bare spots resulting from such damage can and do corrode rapidly.

Galvanic cells are also found when a short length of new pipe is inserted in an old rusty line, when steel rivets are used in fastening copper, or monel sheets, where steel tanks are used on brass radiators and in countless other instances of dissimilar metal couples.

If on the other hand the cathode area can be reduced by applying a coating to it or by substituting a more anodic metal, the magnitude of the galvanic cell will be reduced and likewise the corrosive attack. Insulating the dissimilar metals from each other also provides a possible solution.

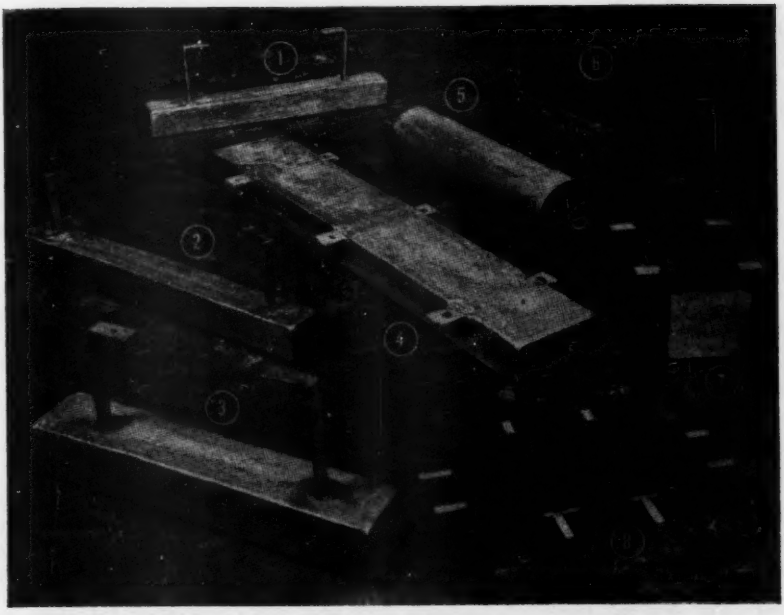
Where these suggestions cannot be applied effectively for one reason or another a galvanic anode system is a logical method for consideration.

MAGNESIUM ANODES

Magnesium anodes are made in a number of different sizes and shapes to fit particular applications. Weights vary from 5 to 160 lb. and each anode has a cast-in steel core by which it is fastened to the structure to be protected either through welding, bolting, or the use of a connecting wire. A number of these anodes are illustrated in Fig. 3.

The steel core is an important part of the anode. It must be bonded properly to the magnesium alloy and the connection between the anode core and structure to be protected must have a minimum of electrical resistance. For this reason, welding is preferred as a means of attachment wherever possible. Bolted attachments are always subject to loosening by vibration and where the bolts pass through the anode some current is wasted in protecting the bolts and the necessary holes in the anode tend to encourage abrading of the anode by the swirling action of the sea water.

In ballast tank applications, anodes with cast-in steel hangers are used so that when installed, the anodes will stand off from the surface to be protected. This is done to reduce the local action adjacent to the anode and thereby provide better current distribution. The calcareous deposit laid down is indic-



1. 42-lb tanker anode, 4 × 4 × 36 in., 24 in. centers
2. 44-lb tanker anode, 4 × 4 × 38 in., 30 in. centers
3. 50-lb tanker anode, 5 × 5 × 30 in., 20 in. centers
4. 160-lb bilge keel, 4 × 10 × 60 in.
5. 100-lb pier anode, 8 in. diam × 32 in.
6. 55-lb hull anode, 7 × 7 × 18 in., 1¼ in. pipe cores on 10 in. centers
7. 55-lb hull anode, 7 × 7 × 18 in., 1½ × ¼ in. strap cores on 10 in. centers
8. 22-lb hull anode, 2 × 10 × 20 in., ¾ × ⅛ in. strap cores

Fig. 3 Types of magnesium anodes for ship application

ative of a polarization of the steel surface. Some current, though in reduced amount, will continue to flow to those areas.

On exterior hull surfaces, the anodes of necessity must be fastened directly to the structure of the ship. Accordingly, an insulating blanket of asphaltum, rubber or other material is installed between the anode and the hull surface to reduce the local action immediately adjacent to the anodes. This can be done in the field or can be factory applied by bonding a layer of asphaltum to the anode surface which will face against the hull. This coating can be softened with a torch at the time of installation and thereby provide a snug fit which compensates for minor curvatures or surface imperfections in the hull plates.

The accompanying illustration showing test anodes attached to steel plates by bolting and by welding both with and

without insulation presents graphic proof of the desirability of insulated and welded attachment (Fig. 4).

Both anodes without an insulating blanket between the anode and the steel plate show more rapid attrition. Both anodes attached by simple bolting show concentrated attack adjacent to the bolts and, in the case of the bolted anode without an insulating blanket, the anode has become loose to the point of being ineffective.

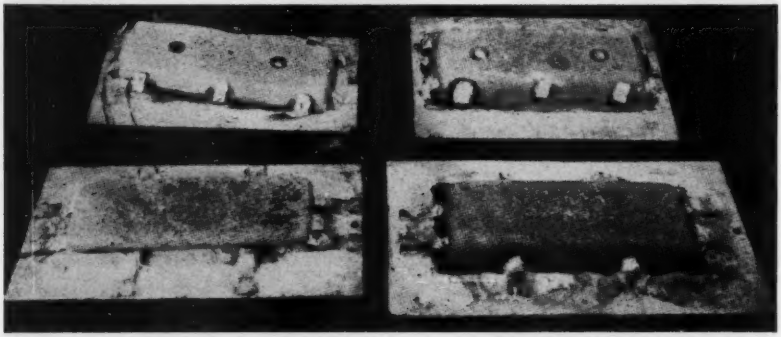


Fig. 4 Effect of attachment method and barrier blanket

(Top left anode-bolt holes enlarged from corrosion so bolt heads pass through holes. Lower left anode-magnesium just barely hanging to steel straps which have been undermined completely. Top right—some corrosion around bolt holes but still tight. Lower right—excellent condition. Best life expectancy. Test plates with sample 22-lb. magnesium anodes attached to a large cathode and exposed in moving sea water at American Smelting & Refining Company plant dock, Perth Amboy, N. J.)

LOCATION OF ANODES ON HULL

The location of anodes on a hull merits some attention from naval architects from the point of view of streamlining, strength of attachment and abrading effect of the water. Whether the anodes be installed directly on the hull surface, on the bilge keel, or in specially provided recessed areas, is of more concern to the shipbuilder or operator than to the corrosion engineer for he is interested primarily in placing anodes where good current distribution can be achieved. There is, however, apparently no serious conflict here.

The number of anodes required to protect a given structure in a particular environment can be determined readily by a corrosion engineer and a protection system can be designed to provide a suitable anode life.

LIFE OF ANODES

Sea water is an excellent conductor and current will flow readily from the anodes to those areas requiring protection. Installations of magnesium anodes in ballast compartments are being designed to give an anode life of 2-3 years, while on a vessel hull a life of 1-2 years can be expected.

For example, in a T-2 center tank 76 42-lb anodes have been used to provide protection for approximately 30 months on a ballasting cycle of 10 days out of every 30. Likewise, a wing tank would require 44 anodes. The outside hull surface of a T-2 tank with an average paint job would require approximately 100

55-lb anodes to protect the ship for 18 months. For tugs, barges and other vessels, requirements will vary with surface area, type of water, condition of paint, speed of the vessel, and so on. It is thus difficult to set down a definite set of rules to follow, yet relatively easy to install a system, which will provide adequate protection and then to adjust it at the first annual docking.

Over-protection can cause blistering or stripping of some paints adjacent to the anodes, but even when this occurs cathodic protection is afforded to those areas so no damage is done by corrosion. Properly applied vinyls are very resistant to such blistering. In some cases where the paint coating is in excellent condition and the current requirements are low, properly designed zinc anodes will afford protection with no danger of damage to paint films. On the other hand, if current requirements are high as on a bare hull or one with paint in poor condition, it may not be practical to install the necessary number of zinc anodes to provide the required amount of current. Zinc anodes also must be of proper design and composition.

PRECAUTIONS

As in the installation of most equipment or processes on shipboard, there are some precautions to be observed. In applying cathodic protection to ballast tanks the question of hydrogen evolution must be given consideration. Any type of galvanic cell and any type of cathodic protection set up to provide protection to steel surfaces will evolve hydrogen, regardless of the type of metallic anode used or equipment used to supply current. Thus under no circumstances is it recommended to install cathodic protection in a tank or other compartment which is improperly vented or in which ballast is carried at anything less than its capacity. This, of course, is in full accord with good shipboard practice.

Magnesium is an active metal chemically. It is this property which makes it suitable for use in a cathodic protection. Magnesium and magnesium alloys will burn when heated to their melting point (approximately 1100 F) in the presence of oxygen. Thus the danger of igniting a substantial chunk of metal such as an anode is remote. On the other hand, fine chips, shavings or dust from grinding magnesium can be ignited quite readily. The metal when heated to its melting point until ignition has been effected will burn with a brilliant white flame and is difficult to extinguish with water. The same may be said for gasoline.

It would be quite possible for a workman, if so inclined, to strike an arc by applying an electric welding torch to a magnesium anode. This, of course, would result in localized melting of metal as it does with steel and in the case of a magnesium a brilliant white light would result. Withdrawal of the electrode would extinguish the flame immediately. The likelihood of sustained burning by virtue of continued application of the electrode is thus extremely remote by virtue of the brilliant white light produced and the likelihood of heating the anode to a point of sustained burning is likewise still a more remote possibility.

Storage of magnesium anodes presents no unusual fire hazard. It is generally recommended that magnesium not be stored adjacent to other combustible materials for which a more real fire hazard exists and which if ignited and allowed to burn freely for a protracted length of time might then ignite

magnesium stored nearby and thereby add further fuel to an existing conflagration.

The foregoing information is submitted for the purpose of being thoroughly familiar with a material which is being handled. Magnesium is not regarded as a hazardous material to handle.

The use of cathodic protection as a means of protecting buried or submerged steel structures has developed rapidly during the past few years. Over six hundred active and reserve vessels are currently being protected with magnesium anodes. It represents an effective, economical method of controlling one of the most destructive forces in our industrial civilization.

THE DIFFRACTION GRATING AS APPLIED TO THE HARNESSING OF WAVE ENERGY FROM THE SEA

LIEUTENANT J. R. GOODYKOONTZ, USNR

THE AUTHOR

is a native of El Paso, Texas, and a graduate of the U. S. Naval Academy in the class of 1944. During World War II he served in the gunnery department of USS *Ranger* and USS *Quincy*, and during the early post-war years was communications officer of USS *Mindoro*. He resigned from the Navy in 1947, took a postgraduate course at Rice Institute, and is presently employed in the A&OS Division of the General Electric Company in Schenectady, New York.

In the reception of wave energy it is frequently advantageous to gather the energy from a relatively large region and by some kind of focusing action to concentrate it into a much more limited region before attempting to utilize it. This focusing action is achieved in optics by lenses or by mirrors. Similar means are used in radar and in sonics. The net result of the focusing action is an intensity increase, or gain, and it is this gain that spells the difference, many times, between a device which is practical and one which is not.

It would appear then that if serious consideration is ever given to the harnessing of the energy of sea waves the possibility of obtaining a focusing action should not be overlooked. Perhaps it is this additional step which would render the utilization of the vast energy of the sea waves a practical reality.

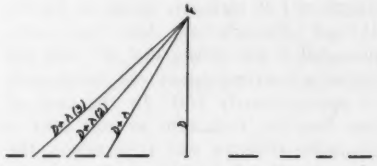


FIGURE I.

One means of focusing which is not widely used outside the laboratory is the diffraction grating. The principle of the diffraction grating can be found in any college text on fundamental physics and need not be discussed here. Rather we will consider a particular type of diffraction grating as shown in Figure I.

Here the slots are arranged so that they vary in distance from the focal point F in increments of whole wave

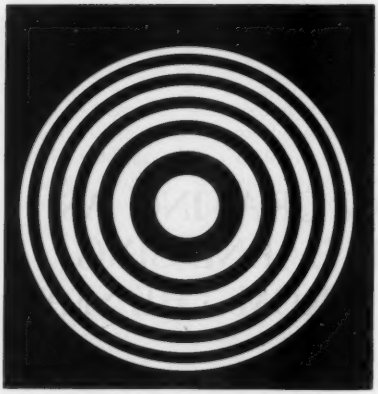


FIGURE II.

lengths λ. Thus waves arriving at F are in phase and so are additive; and although about half the incident energy is blocked by the grating the intensity at F is much greater than if the grating were absent. Optical lenses of this type have been made and found to function according to the theoretical predictions. A microwave defraction lens for a wave length of 1.26 inches is shown in Figure II and although very few rings were provided it was found that the lens did act as a focusing agent and had a gain of approximately 160. In the case of this lens the reduction in cost over a parabolic reflector was tremendous, the cost reduction being due to the extreme simplicity of construction. However, use of such a low gain device, regardless of its simplicity, is not warranted in a radar system and the device is of interest only in that it demonstrates that a significant gain may be achieved with the employment of relatively few rings.

But unlike a radar system, a system designed to harness the sea must have simplicity of construction almost above all else. It must defy the elements for long periods of time. If a focusing structure is to be made for the sea it is probable that the diffraction grating affords the only practical means of doing so.

Of course a parabolic sea wall could be made which would effectively focus the waves. However such a solid, mammoth wall would be expensive and further the power extractor would of necessity be situated on the seaward

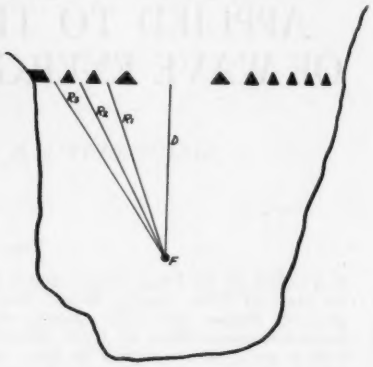


FIGURE III—$R_1 = D + \lambda$, $R_2 = D + 2\lambda$, $R_3 = D + 3\lambda$.

side of the wall making it vulnerable to storms and inconveniently removed from the land. Moreover a smooth wall, and smoothness here would be essential, is not a desirable feature in a seawall since it provides negligible damping action and suffers wave impacts at their peak force.

By contrast, the elements of a diffraction grating need not reflect but may be coarse and absorptive. Such a system is shown in Figure III. Here rough concrete baffles have been erected in the sea in a line parallel to the incoming waves. The gaps, spaced as indicated on the figure, admit wave sections which converge at F provided they are of the proper wave length. The value of λ must be obtained by observation at the site. Of course λ will not remain exactly the same at all times but in certain locations it should remain fairly

constant throughout most of the year. During storms λ undoubtedly will change but this is an advantage since the grating, being frequency sensitive, will tend to block all waves except those of the particular frequency for which it was designed. Thus the shore side of the grating will be sheltered to a degree from the larger storm waves.

With an installation such as this we should have at F a magnified, localized wave. It is here that the power from the sea must be extracted. No unique solution is offered for doing this, the problem being a difficult but straightforward one of converting the oscillating wave motion into a usable form. In general this would require that a buoyant body be placed at F and connected by levers to a stationary platform. The buoyant body following the vertical rise and fall of the amplified wave would be made to drive pumps via the levers and the pump output in turn used to drive a generator or other suitable mechanism.

The grating in Figure III is straight. However gratings may be made in any form although the spacing computations become involved when other than the straight or circular form is used. A circular grating is shown in Figure IV.

FIGURE IV.

This form might be useful along straight coast lines.

Whether or not the diffraction grating can actually be applied, in a practical manner, to the focusing of water waves is something which must be determined experimentally in a test basin. Assuming such experimentation turned out favorably, a revolution in power production would not necessarily follow. Certainly more convenient and adequate sources of power exist. But there are places in the world, such as island bases in the Pacific, where there is no natural source of power and all fuel must be imported. Here there is an abundance of waves. Here the harnessing of the seawaves by means of the diffraction grating might be applied to advantage.

BALANCING TURBINE-GENERATOR ROTORS

ACKNOWLEDGMENT

This article was written by MR. L. P. GROBEL of the Turbine Division of General Electric Company. It was published in the July 1953 issue of "General Electric Review."

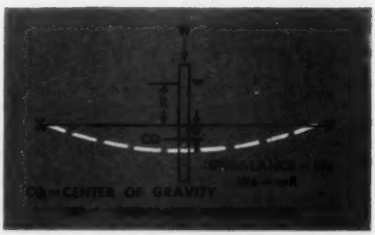
Large steam turbine-generators—some large enough to supply a fair-sized city with electricity—run weeks or months without letup. And among the factors contributing to this remarkable performance is *vibration-free* operation.

An unbalanced rotor is the common cause of vibration. Its coupled length—turbine rotor plus generator rotor—in today's high-speed machines may be 80 feet or more with its weight exceeding 200,000 pounds. And so you can readily appreciate why low amplitudes of vibration are essential to the large turbine-generator.

To get these low amplitudes, we use a method known as *precision balancing*. Here, the ideal is perfectly balanced rotors before the assembly and shipment of turbine-generators. Although it's not a small chore, we've nearly realized this ideal by careful manufacture and balancing of turbine and generator rotors.

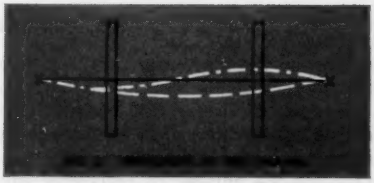
CAUSE AND EFFECT

The simplest type of unbalance occurs in a thin wheel (Fig. 1) on a shaft. Assume the shaft to be weightless and the wheel's center of gravity a distance e from the shaft center. Then the unbalance is equal to the product of the weight W of the wheel and its eccentricity e. If the wheel and shaft were placed on level ways, the gravity effect of the unbalance would cause it to turn and come to rest with the unbalance at the bottom—a simple example of *static* unbalance.

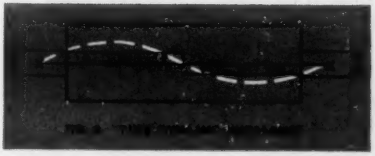


When the wheel rotates, centrifugal force of the unbalance deflects the shaft in the single-loop form shown as a dashed line. Because the deflection rotates with the shaft, it appears as a vibration. To balance the wheel, a balancing weight w is placed a radial

distance R from the shaft center and 180 degrees from the unbalance. The weight is such that $We = wR$.



To go one step further, let's consider a rotor having two wheels (Fig. 2) that are out of balance. If both their eccentricities are equal and in the same angular position, the rotor is statically unbalanced and will run in single-loop form shown by the dashed line. This situation is best corrected by using two equal weights, one in each wheel, to form a static pair defined as two equal weights at the same radius and angular position.

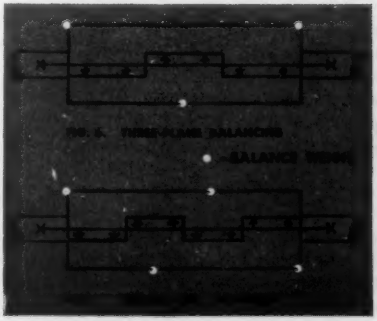


If the individual wheel eccentricities are 180 degrees apart, the rotor is balanced statically but not dynamically. When running, the rotor will be deflected in the two-loop form shown by the broken line. Such unbalance is normally corrected by putting equal weights in each wheel, at the same radius and 180 degrees apart.

Pure dynamic unbalance of a turbine or generator rotor (Fig. 3) will cause the two-loop form of vibration. These unbalances are 180 degrees apart, and the product of the weight and eccentricity of one-half the length is equal to that of the other half.

Higher forms of vibration can be incited in long high-speed rotors by unbalances of the three-loop type (Fig. 4) and the four-loop type (Fig. 5).

In general, static and dynamic unbalances are corrected by placing balance weights in two balancing planes near the ends of the rotor span. Unbalance of the three-loop type, however, requires three-plane balancing (Fig. 6) to correct for the unbalance of each section. Correspondingly, the four-loop type of unbalance requires four-plane balancing (Fig. 7).



WHY PRECISION BALANCING?

Rotors are balanced on sensitive balancing machines at low speed. In one type the rotor is supported on spring-mounted bearings and run to a critical speed for maximum vibration. Data on the amount of unbalance and where to place the weights are then read from the machine. Because the rotor is relatively stiff at low speeds, unbalances will be only vectorially counterbalanced. Long rotors will not be in balance when run at higher speeds—unless the balance weights are in approximately the same plane as the unbalances.

To illustrate this, let's assume that a rotor has an unbalance midway between its two end planes. The low-speed balancing machine will indicate a balance-weight correction at each end plane equal to one-half the unbalance and 180 degrees from it. But when the rotor is run at a high speed, the centrifugal force of the midspan unbalance will cause a greater shaft deflection than the centrifugal force of the two end corrections, since they are near the end of the rotor span. This difference in deflection will appear as vibration.

Neither can satisfactory correction be made for distributed unbalances in a high-speed rotor when it is assembled in the turbine-generator. For the only balancing planes then accessible are those near the ends of the span.

Prior to our current practice of precision balancing, it was occasionally necessary—and more frequently desirable—to disassemble a machine to correct a midspan unbalance. Roughly, the procedure was: 1) initially balance the rotor in a low-speed balancing machine; 2) assemble the rotor in its own bearings and balance it for distributed unbalance; 3) calculate midspan unbalance and remove rotor to compensate for it, and 4) reassemble the rotor.

As high-speed rotors (3600 rpm) were built larger and longer, we wanted to make accurate and nearly complete correction for distributed unbalances in less time. As a result turbine rotors are now produced virtually free of distributed unbalances by manufacturing them with a high degree of precision.

For generator rotors, however, with their assembly of heavy coils and other parts, accurate manufacturing is not enough. After assembly, precision balancing is completed by balancing them throughout their lengths.

Turbine-generator rotors are designed to have low sensitivity to unbalance. These designs are determined from card-index calculating machines that take into account the effect of flexibility of supporting members in depressing critical speeds below rigid support values. (Critical speeds occur when rotational speeds equal some resonant frequency—deflection of the rotor will be a maximum at that point. A large 3600-rpm machine, for example, has several critical speeds within the running range.)

As a point of interest, critical speeds aren't dangerous. Most modern machines are so well balanced that careful observation is necessary to detect the presence of one. However, since sensitivity to unbalance is a maximum at critical speeds, turbine-generators are designed to have an appreciable spread between their rated speed and any critical speed.

BALANCING TURBINE ROTORS

A thermally stable turbine rotor will operate over the wide range of steam temperatures that it is subjected to with insignificant distortion or bending. This is essential so that the rotor remains in balance at all temperatures within the load range. Testing and heating rotors for high-temperature service

to assure thermal stability are therefore important items in precision balancing.

Thermal instability arises because of mutilation of steel crystals on the rotor's surface during machine work. This causes some variation in the rate of heat transfer—and expansion—at the rotor's surface. To overcome this the rotor is tested and cured in a heat lathe after all machine work within, and adjacent to, the shaft span is completed. In the heat lathe the shaft undergoing test is heated to a high temperature—and slowly cooled—to eliminate the surface strains.

Turbine rotors for low-speed machines (1800 rpm) are usually of the built-up type with bucket wheels shrunk onto the shafts. But large high-speed rotors have their bucket wheels machined integral with the shaft forgings. Treatment of either type for unbalance differs: Bucket wheels are balanced before being shrunk onto the built-up rotor shaft. Solid-type rotors, on the other hand, are nearly symmetrical; because they are accurately machined, the unbalance of shafts and wheels will be small in most instances.

Great care is taken to minimize unbalances that might be introduced in the assembly of buckets on a rotor. Here again, unbalances are eliminated in one of several ways, depending on the type of rotor and size of buckets. The longer and heavier low-pressure buckets are weighed in a moment balance. This takes into account the weight distribution along their lengths. Moment weights are then charted, and from this data the buckets are assembled on the rotor for minimum unbalance.

With high- and intermediate-pressure turbine rotors having short buckets, accurate corrections are made for any known unbalance in bucket wheels. However, experience has shown us that short buckets are so nearly the same in weight that there's no advantage in weighing and charting them.

Completed rotors are balanced at low speed in a balancing machine having high sensitivity. Then they are assembled and turbines run at rated speed. Most turbines will have such low amplitudes of vibration it will be immediately evident that the rotors are in nearly perfect balance.

BALANCING GENERATOR ROTORS

The procedure in precision balancing of generator fields is necessarily different from turbine rotors. Fields are usually much longer and heavier—as are some individual parts in the field assembly. (A large 3600-rpm field may be over 30 feet long and weigh more than 100,000 pounds.) Machining and assembly operations are carried out to manufacture them in as good a balance as possible. They cannot, however, be assembled with perfect balance.

Alternate-slot milling of the field-coil slots is one practice we use to improve balance. The slot milling machine simultaneously cuts two slots 180 degrees apart. After each pair of slots is cut, the field is turned 180 degrees less one slot pitch to mill the next pair of slots. Small differences in slot dimensions are thus counterbalanced.

After slotting, and after the major part of machine work between bearing spans are completed, the largest 3600-rpm fields are tested in a heat lathe. The test procedure differs from that employed with the turbine rotors, but the objective is the same—to assure thermal stability of the field. A field is first checked in the heat lathe over a temperature range several times greater than its operating range. If it is shown to be thermally stable—as indicated by its nearly unchanging deflection—the rotor is removed from the lathe. If not stable, it is heated to a higher tempera-

ture to remove the surface strains. And after cooling, it is checked again for thermal stability.

Before windings are assembled, the field is balanced and correction made in its body portion. Appreciable unbalance is corrected by machining metal from the field or from its ventilating-slot wedges. Next, wedges for each coil slot are weighed. Calculations are made to determine unbalances that may result from their weight and angular differences around the field, and suitable corrections are made. Field coils are also weighed and assembled to give a balanced arrangement. This practice aids in attaining thermal stability because heating of the field coils is then effectively symmetrical. (The I^2R loss of a coil varies inversely as its cross section. If the cross section is not uniform, heating will not be uniform.)

Precision balancing is completed in a balancing pit. This setup permits making accurate corrections for unbalances that may be distributed irregularly along a rotor length. To accommodate fields of different lengths the pit is furnished with bearing pedestals that can be moved on ways. After a field is assembled in the bearings, a cover is placed over the pit. Heat generated by the field's windage is removed with cool air circulated by a closed ventilating system. The 3600-rpm fields are driven by a 3600-rpm steam turbine. When 1800-rpm fields are balanced, a two-to-one reduction gear is interposed.

HOW BALANCING IS DONE

Balance weight corrections in the body portion of a generator field are made by changing sizes of balance plugs located in the field poles. Full-length plugs are installed initially and weight changes then made by unscrewing them and installing plugs of shorter lengths.

The arrangement of balancing plugs in a relatively small field is such that a row of plugs is near each end of the pole face; the opposite pole has a duplicate set. Thus, four rows of plugs permit balance weight corrections at any desired angle.

Long fields will have at least twice as many plugs in each row with a somewhat different distribution than that shown. On the other hand, four pole fields have a single row of plugs along the center line of each pole face. This way, plug changes in either one or two rows will give balance weight corrections at any desired angle.

Balance weight planes are provided in the field's fan ring and ring-centering rings (Fig. 8) so that there are two balancing planes between each bearing and the rotor body. Additional balancing planes are also provided in the coupling and collector-end shaft extensions.

CUT AND TRY

In balancing, a rotor is brought to speed, and vibration amplitudes of shaft, bearings, and balancing machine data are taken. It is then brought to rest and the desired balance weights installed for the first trial. Run again to balancing speed, data are taken as in the original run. From these two runs, the data are used to determine the disposition of weights for the next trial. This procedure is continued for several runs until maximum improvement is obtained with a given type of balance correction. Next, another type of correction is made and the process repeated.

At first glance you might think this a long roundabout procedure. Actually, the method simplifies and minimizes the work. For one thing, a given correction can usually be made in two or three

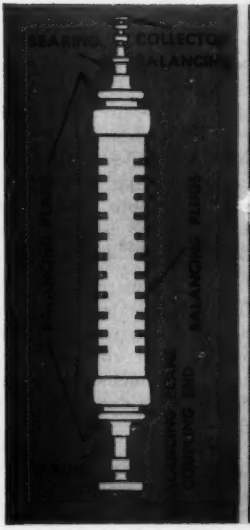


Fig. 8. Various positions accessible on generator rotor for balance weight corrections.

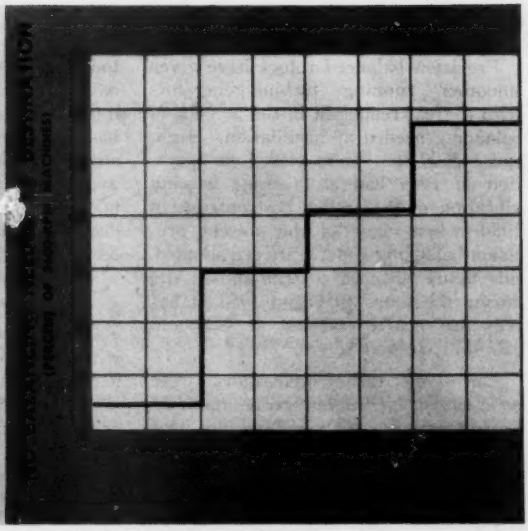


Fig. 9. Practical effect of precision balancing at factory. During 1952, 58 percent of all turbine-generators shipped needed no further balancing at destination.

balance trials. For another, if you try to correct several types of unbalance at once, your chance of doing so is remote; correction for each type must be accurate in both magnitude and angular location. Then, too, this method takes advantage of the fact that vibrational response at certain speeds is much greater for one type of unbalance than another. For example, the response to static unbalance will be greatest at some low speed because other types of unbalance will have little effect. At a higher speed, however, the vibration caused by dynamic unbalance will be greatest so that dynamic balancing can effectively be carried out.

A fairly well standardized procedure is followed in making successive types of corrections. A field is first balanced statically with a static pair. This may be considered two-plane balancing to virtually eliminate single-loop vibration.

Two-loop vibration caused by dynamic unbalance is then corrected with a couple. A sufficient number of static and dynamic balance trials are made until maximum improvement in vibration is obtained. This must be evidenced by data at lower and normal speeds.

In the next step, fields are balanced to correct for three-loop form of vibration. Balancing in three planes is required. Trials are conducted in the same manner as two-plane balancing, except that it is done at the rotor's rated speed. In three-plane balancing—as with all multiplane corrections—it's desirable to use weights of proper relative size, placing them symmetrically in the rotor to maintain the static and dynamic balances you already have.

The next and final step is running the balanced field in its own armature. Vibration of the field and stator are observed during these electrical and mechanical tests. Refinements, if needed, are made then.

WHAT ARE THE RESULTS?

Precision balanced rotors have given smoother running turbine-generators with a great reduction in the amount of balancing needed at installation. High-speed 3600-rpm units placed in operation in 1949 had an average bearing vibration of 0.42 mils. By contrast, in 1950, when many of the present precision-balancing practices were adopted, this figure dropped to 0.30 mils. And during the years 1950 and 1952, it has remained nearly constant at 0.26 and 0.27 mils, respectively.

The 1949 turbine-generators were good machines. Current reduction of 35 percent in vibration simply means that today's precision-balanced machines have still less vibration. Over the same four-year period—1949 to 1952—there has been a decided reduction in the amount of balancing at destination. An average of 7.4 balancing trials were taken on the 1949 machines; this figure decreased to 5.2 a year later, became 2.4 in 1951 and 2.0 in 1952.

The most striking illustration of this is Fig. 9. It shows the percentage of 3600-rpm machines placed in operation with such low levels of vibration they needed no further balancing—convincing proof of the effectiveness of precision balancing.

DISCUSSION

BY

CAPTAIN J. A. BROWN, U.S.N.

OF

ACCENT ON ACCESS—THE 'INS' AND 'OUTS' OF MACHINERY SPACES

JOHN R. WRIGHT

JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC., MAY, 1953

The discussion of the design requirements for access into machinery spaces presented by Mr. Wright is certainly worthy of careful reading by all naval engineers interested in the design of warships. The access from topsides to the machinery spaces below is not only where the deck hand and the water tender separate, but where the naval architect leaves off and the marine engineer takes over the arrangement responsibility. Here is one of those nether-nether lands where the responsibility may be assumed by either and may just as likely not be assumed by either. The naval architect is involved in the arrangement of the living spaces, store rooms, the structure, and the damage resistance of the hull. He realizes that the black gang must have access to the machinery spaces, but it must not interfere with the naval architectural features. Likewise, the marine engineer is primarily interested in the design of the most efficient and dependable power plant possible. He is sure to consider access to boilers, room to pull superheater tubes and the like, but again the compartment access—that can be attended to later, and isn't that the responsibility of the naval architect anyway?

The setting up of a set of design criteria for these important thoroughfares aboard Navy ships is, therefore, most significant. Especially so, when we consider the large numbers of trained personnel who must depend on them not only for normal access but for escape in case of serious casualty. The loss of one of these lives unnecessarily would be a tragic blunder and the jeopardizing of a machinery space crew would be unforgivable. The designer must consider these ins and outs as carefully as if he himself were expected to be stationed in these spaces in battle.

While enthusiastic about most of the ideas presented by Mr. Wright, I would like to disagree with him on a few minor points and add a few thoughts of my own. I question the advisability of bolted plates in general. They are extremely difficult to make tight; fabrication is expensive and installation and removal is time consuming and expensive. Furthermore, they can never be depended on to be as strong or tight as the intact plating under severe distortion due to explosions. In most cases the burning out of the plate and rewelding will prove cheaper and is far more dependable. Let's not install bolted plates in warships.

Second, why do we need any doors opening into the emergency escape hatches? Any door, no matter which way it opens, is liable to jamb just when it is needed most. An open archway would appear to be more satisfactory.

Flooding up through the trunk is of no consequence since there are no openings from it to spaces below the waterline. And if a few feet of water were to leak into the trunk, due to slow leakage, the door might act as a check valve. This might prevent opening the door, whereas the water could be easily taken care of by the bilge suctions if the door were removed. Flooding of the machinery space down the trunk is quite unlikely if the trunk is kept well in from the skin of the ship. Therefore, let's make it a true emergency escape that cannot be blocked.

The 18″ scuttle does have its limitations, but why not use the standard machinery escape hatches? According to the Standard Plans these come in the following sizes: 18″ x 30″, 24″ x 30″, and 24″ x 36″. There is not much advantage in a 25″ scuttle over the 18″ x 30″ hatch, and the latter is easier to accommodate, particularly from a structural point of view.

The requirement that the upper ends of the various access openings from one machinery space be located in different watertight compartments is probably going to be impossible to meet on most ships, since the transverse subdivision of the machinery spaces is carried vertically to the main deck. Furthermore, there is a growing trend to eliminate longitudinal subdivision to reduce the hazard of unsymmetrical flooding. I suggest that it is more important to see that the escape hatch is not located in a compartment which can ever be locked or otherwise secured. That is, the escape should not be located in an office, workshop, scullery, nor near the end of a deadend passageway. These accesses should be located so that escape fore and aft and topside is easy. On a DD or DE the escape hatch should be in a main passageway near a door in the deckhouse side or a ladder leading to the 01 level. Locating these escapes in the open deck is probably not advisable due to the possibility of contamination by radioactive material.

I am delighted that Mr. Wright has thought about this problem long enough and carefully enough to establish this set of tentative requirements. I hope that all engineers who are involved in the arrangement of our warships will study carefully his recommendations and develop more ideas which will make access to our machinery spaces easier in normal operation and safer in time of emergency. This is a very important design feature, but one which may easily be forgotten in the development of a design.

★ ★

BY

LOREN G. MAXWELL

OF

"THE PHENOMENON OF STATIC ELECTRICITY"

CAPTAIN CARL J. LAMB, USNR

JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC., MAY, 1953

I have read with interest the article on "The Phenomenon of Static Electricity" in the May JOURNAL of the American Society of Naval Engineers, for which I would like to offer a few comments. I gain from the article the general impression that probably any electricity in which the safety aspect is concerned is due primarily to the generation of static electricity.

This may be an erroneous concept. It is true that static electricity may be responsible for the generation of an electric discharge if there is no ground connection, if a charge at a high potential exists, and if current leakage is low through the insulating materials. The proper ground connection of course partially eliminates this hazard.

However the article observes that the ground connection may become a source of hazard, if it is not handled correctly. I suggest that sparks or discharges are also involved which are due to causes other than static electricity, when metal connections occur between a vessel and shore. Within shipyards under various conditions I have observed the flow of currents which are not necessarily static. Such currents flow because of a difference in potential between the ship (even in conducting salt water) and the shore, and range from a few milliamps in grounded connections to hundreds of amperes, in serious cases. These currents may be due to improper welding installations aboard vessel, shore power connections, other stray currents, and electro-chemical potentials between the vessel and shore. I have observed all of these types of currents during electrolysis investigations on vessels of the Navy. It is my opinion that a spark may occur due to a relatively low difference in electro-chemical potential; and stray currents which may be measured on almost all vessels. This potential also varies by location. A particular hazard exists where these currents exist, when a ground contact is made.

To provide a method of stressing the importance of the hazard and to provide more information on the subject, I believe it would be reasonable to add a meter in the ground circuit which is connected before fuel filling operations are begun. This would give even the most unexperienced personnel a means of observing serious currents. Within limits of a certain milliamperage, fueling operations should not be continued. The most important aspect of observing current flow would be to note currents which will occur in a ground connection when breaks occur in a hose connection, or the ground connection. If casualties occur due to this cause currents should be limited in value. The flexible ground connection should also be made as close as possible to each side of the hose connection because a parallel path for the flow of current exists. This spark will invariably occur on breakage of a line and ignite a liquid flowing in it, unless a flexible ground is provided with sufficient length where breakages may occur.

A suitable means for measuring the current may be provided by obtaining a small 50-0-50 range inexpensive millivoltmeter with the zero position in the center of the scale, and a 5 ampere, 50 millivolt shunt. These instruments may be installed in a small box which is used to mount a ground disconnect switch.

This means of locating and observing both currents and proper ground connections is inexpensive and is believed would be well justified for minimizing existing hazards. It is hoped that the above comments may further the solution of the problem.

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BY

J. BARRAJA-FRAUENFELDER

OF

WORSHIP OF THE BMEP AND THE NEW MAN ENGINE

P. H. SCHWEITZER

JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC., AUGUST, 1953

In the August 1953 number of the Journal, there appears an article by Prof. P. H. Schweitzer, on the issue of BMEP, entitled "Worship of the BMEP and the new MAN engine," in which reference is made in the concluding paragraphs of BMEP's obtained by various other engines.

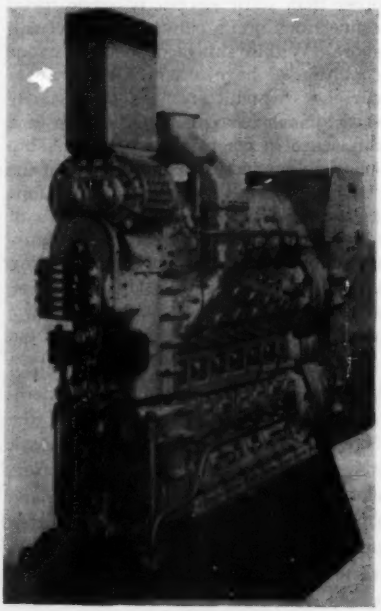
Since these other BMEP's range from .326 to .355 lbs./HP/hr., it will not be out of order to mention one other which has so far been lost in the shuffle, because after the first pilot engine was built and tested, was never put into production because of the manufacturer's aversion to undertake another size design and build a pilot engine before manufacture was initiated.

I refer to the experimental engine designed and built by myself for the Bureau of Engineering in 1933 and delivered in 1935 as the files of the Bureau may disclose.

This engine was an opposed piston, two cycle, port scavenging and port exhaust of 6½" bore by 9¾" stroke and developed its contract HP of 525 at 650 RPM. Although this engine during builders trials gave a much greater output, this was the official and recorded rating as shown in the Instruction book.

At the official trials, the following were the results:

240 hours continuous 457 BHP—
650 RPM—Fuel .354 #BHP/hr



4 hours continuous 513 BHP—
650 RPM—Fuel .358 #BHP/hr

24 hours continuous 513 BHP—
650 RPM—Fuel .349 #BHP/hr

During the 24 hours test when the best fuel consumption was verified, the scavenging pressure as delivered by the Root blower was recorded at 2# 7 oz.

p.s.i. This, I consider rather good for a two cycle port engine.

I show a photograph of the engine and the following quotation from the then Commander Lisle Small, which is self-explanatory, and I trust that this example is of sufficient interest to add it to the record.

"My dear Mr. Frauenfelder:

. . . . . "Let me say, and I do not care if I am quoted, that I think it was a very remarkable thing that your engine ran through these severe tests of long duration, (ten days non stop) without a single shut-down or adjustment of any kind, not even a loose nut or screw. Furthermore, it is even more significant that the fuel consumption and lubricating oil consumption did not increase as the test progressed.

Yours very truly
Signed: L. F. Small,
Commander, U.S.N."

GENERAL CHARACTERISTICS AND RATING
OF
SPECIAL LIGHT WEIGHT SUN ENGINE
TYPE: 6 CYLINDER, S.D.G. 6.5

As per Modified Contract
Bureau of S&A Letter May 6, 1935.

Bore	6-1/2"	Stroke each piston	9-2/4"		Total 19-1/2"
Ratio:	Stroke: / Bore	One piston	1.5	Two pistons	3.0

Piston Speed at Rated R.P.M. of 650—1055'/min.

Guaranteed Rating	—240 Hrs. 300 kw	—450 B.H.P.	—Speed Optional
Obtained on Test	—240 Hrs. 310 kw	—457 B. H. P.	—Speed—650 RPM 4/5 Power +
Guaranteed Rating	— 4 Hrs. 345 kw	—505 B.H.P.	—Speed—675 RPM
Obtained on Test	— 4 Hrs. 352 kw	—513 B.H.P.	—Speed—650 RPM Full Power
Guaranteed max. M.I.P. at full power 105#/sq. in.			—Obt. 93.3#/sq. in.
Type Accept. Test	— 24 Hrs. 363 kw	—525 B.H.P.	—Speed—650 RPM Full Power +

FUEL AND LUBRICATING OIL CONSUMPTION

Guaranteed Rating	—240 Hrs. Fuel	Lub. Oil
Obtained on Test	—240 Hrs. Fuel .354#/BHP/hr.	Lub. Oil .0041#/BHP/hr.
Guaranteed Rating	— 4 Hrs. Fuel .400#/BHP/hr.	Lub. Oil .004 #/BHP/hr.
Obtained on Test	— 4 Hrs. Fuel .358#/BHP/hr.	Lub. Oil .0046#/BHP/hr.
Type Accept. Test	— 24 Hrs. Fuel .349#/BHP/hr.	Lub. Oil .0045#/BHP/hr.

BLOWER CHARACTERISTICS AT 650 R.P.M. OF ENGINE

Cu. ft./min.—1900 Pressure 2#-7 oz/sq. in. R.P.M. 1800

On the basis of these results, the power distribution is as follows:

B.H.P.	513.00	As tested	86.20%
Blower	28.90	As tested	4.85%
Lub. Oil Pump	1.20	As tested	.20%
Salt Water Pump	3.00	As tested	.50%
Fresh Water Pump	1.20	As tested	.20%
Friction	48.00	Residual	8.05%
I.H.P.	595.30		100.00%

CALORIFIC VALUE OF FUEL USED—19,470 BTU/lb.

Thermal Efficiency at 513 B.H.P.

$$19{,}470 \times .358 = 6970 \text{ BTU} - \frac{2545}{6970} = 36.5\%$$

Thermal Efficiency at 525 B.H.P.

$$19{,}470 \times .349 = 6795 \text{ BTU} - \frac{2545}{6795} = 37.5\%$$

Mechanical Efficiency at 513 B.H.P. 86.2%

The remarkable thing about this engine was the high mechanical efficiency, which for the 4-hour Full-Power test resulted as 86.2% which is unusual for a two-cycle engine at moderately high speed.

BOOK REVIEW

METADYNE STATICS

By Joseph Maximum Pestarini

The Technology Press of Massachusetts Institute of Technology and
John Wiley & Sons, Inc.
440 Fourth Avenue, New York 16, New York

415 pages with Illustrations
Published in 1952
Price $9.00

Reviewed by T. S. Huang, Jr.

An increased interest in d-c machine theory has been stimulated in recent years by the growth of feedback control systems. The amplidyne is a familiar development of the dynamoelectric amplifier. This machine is, however, only one version of a more general class of machines which is the subject of "Metadyne Statics."

Dr. Pestarini defines a metadyne as ". . . a machine provided with an armature having a commutator upon which bear at least three brushes per cycle of the machine, commutation being independent of the main windings of the stator or any eventual magnetic member acting upon the armature." The metadyne may be more easily visualized as a d-c machine in which armature reaction controls the machine characteristics through the use of extra sets of brushes, placed between those of the conventional d-c machine.

The book deals with steady state theory, the design and application of metadynes. Rather novel treatment involving the use of analytical devices such as "canonical currents" and "void systems" distinguishes Part I which covers general rules valid for all metadynes. In Part II, which is more than two-thirds of the book, the author investigates special cases of metadynes covering their characteristics as motors, generators and transformers. The transformer metadyne is essentially a device for supplying constant voltage source and vice versa.

Several chapters are devoted to metadyne applications. These machines have been used successfully, mainly in Europe, in such equipment as cranes, electric locomotives and rolling mills. Of particular interest to naval engineers is the description of a metadyne system for deck auxiliaries as installed in several cruisers of the Italian Navy. The ship's conventional direct-current, constant-voltage power system energized a transformer metadyne which in turn supplied a constant-current loop. The deck machinery was driven by motor metadynes connected into this series loop. Certain advantages in simplified switchgear, reduction of cable-weight and less damage from short circuits are claimed for the system.

"Matadyne Statics" had its origins in a manuscript recording Dr. Pastarini's early investigation into a new group of commutating machines which he named "metadynes." In 1930, this manuscript was published in the "Revue Générale de l'Électricité." Since then, graduate courses on metadynes have been instituted at the University of Rome, Massachusetts Institute of Technology, and Columbia University. At present, Dr. Pestarini is a lecturer at the last two institutions.

DIED

The Society has received notice that the following have died since the publication of the August, 1953, Journal:

RADFORD, LAWRENCE, Civil Member

ZORN, HERBERT L., Civil Member

PAUL, JAMES E., Associate Member

CHANGES IN MEMBERSHIP

Announcement is made with much pleasure that the following have become members of the Society since the publication of the August, 1953, JOURNAL.

NAVAL

Fuller, Robert Warren, Lieutenant, USNR,
USS *M. J. Manuel* (DE 351), % Fleet P.O., New York, N. Y.

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Halbach, Carl Richard, Lieutenant, USNR,
USS *LST* 1090, % Fleet P.O., San Francisco, Calif.

Halboth, Henry C., Lieutenant, USNR,
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USS *Randolph* (CVA 15) % Fleet P.O., New York, N. Y.

Neander, Stanley B., Lieutenant (j.g.), USN,
USS *Scabbardfish* (SS 397) % Fleet P.O., San Francisco, Calif.

Pedretti, Charles Donald, Ensign, USNR,
USS *Bayfield* (APA 33) % Fleet P.O., San Francisco, Calif.

Shourd, Walter Richard, Ensign, USN,
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Kennedy, Thomas Albert, Vice President,
Zurn Services, Inc., 140 Cedar St., New York 6, N. Y.

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Branch, Office of Naval Material, Navy Material, Navy Dept.,
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LeGault, Aime Jimmie, President, Port Service Corporation,
601 Degraw St., Brooklyn 17, N. Y.

Schafler, Norman I., President Consolidated Diesel Electric Corp.,
Ludlow and Canal Sts., Stamford, Conn.

Simms, Leslie Eugene, Commander (E) RCN,
Canadian Joint Staff, 1700 Massachusetts Ave., Washington 5, D. C.

Simon, Joseph Patrick, Cutler-Hammer, Inc.,
112 No. 12th St., Philadelphia 7, Penna.

ASSOCIATION NOTES

ORIGINAL ARTICLES

The editor of the JOURNAL is most anxious to obtain manuscripts of original articles on subjects of interest to naval engineers. Any manuscript accepted for publication becomes the property of the Society which copyrights it upon publication. Authors are paid from $40.00 to $150.00 depending upon length, interest and professional value.

The rules for manuscripts are as simple as we can make them.

1. They must be legible (typewritten, double-spaced preferred) since no proof is submitted to authors for correction prior to printing.

2. Single copy only is required.

3. Mathematical formulae used must be set up, preferably by hand printing, so that there can be no question as to symbols, subscripts and exponents.

4. Any drawing submitted must be black on white. A cloth or paper tracing is acceptable but not required.

5. Photographs may be negatives, but glossy prints are acceptable.

6. Include on a separate page a short biographical sketch(es) of the author(s). 50 to 100 words for each author is desired.

Manuscripts should be mailed addressed to:

Secretary-Treasurer
American Society of Naval Engineers
605 F St., N. W.
Washington 4, D. C.

Manuscripts accepted will not be returned unless specifically requested by the author. If returned, they will be in the condition which has resulted from the work of the printer and the engraver. Immediately following publication, the author is furnished 10 reprint copies of his article free of charge. Additional copies may be purchased from the Society if the request is received 30 days prior to the publication date which is the 25th of the issue month. Estimate of cost of additional reprints, which will vary with the nature of the article and the number of copies ordered, will be furnished on request as soon as possible after the article is set up.

Manuscripts not accepted will be returned, postpaid, by the Society.

Manuscripts which are accepted will be published in the earliest JOURNAL which has not yet been closed (60 days before publication) and for which insufficient material is already on hand.

PHOTOGRAPHS

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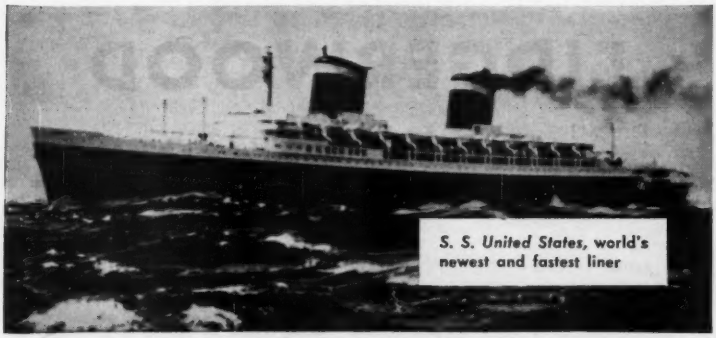

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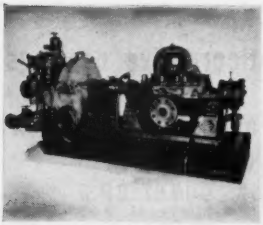

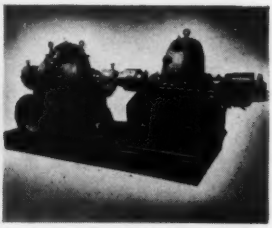

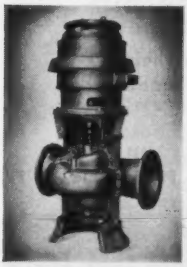
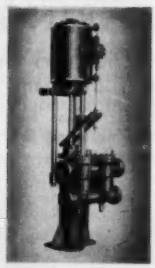
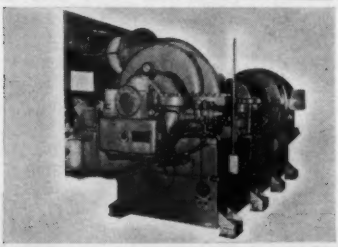
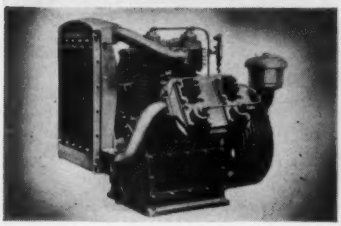

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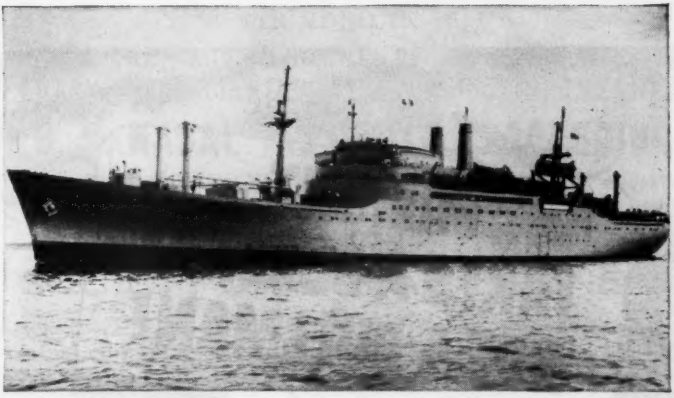

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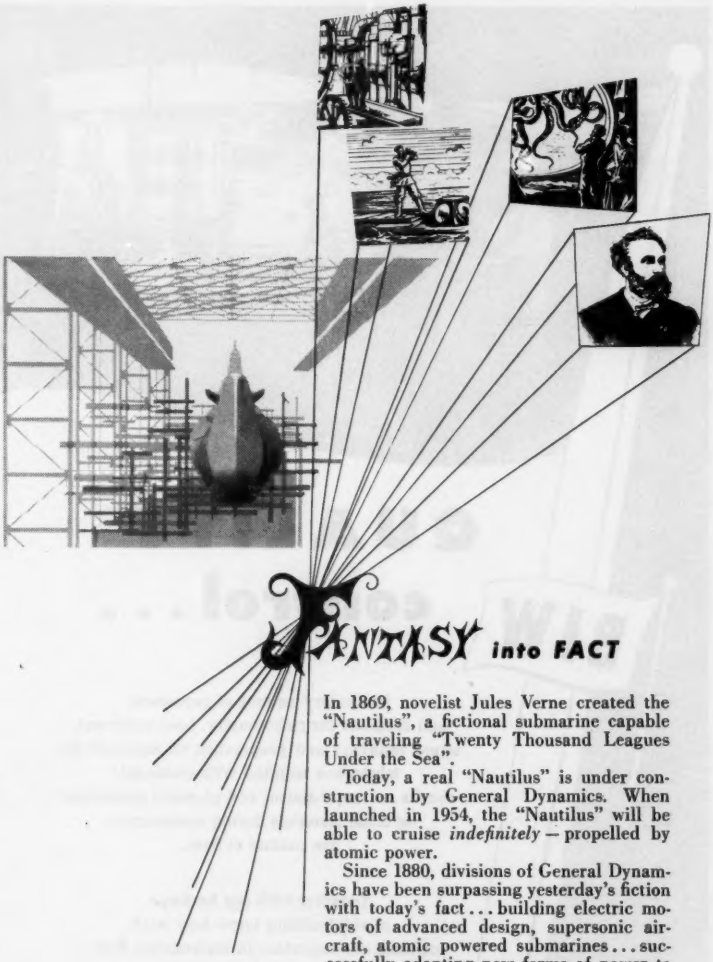

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